WOODHEAD PUBLISHING INDIA IN ENERGY

# Advanced Renewable Energy Systems

## Part I

S. C. Bhatia

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## Part – II

# Preface

Renewable energy is a natural energy which does not have a limited supply. Renewable energy can be used again and again and will never run out. Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources.

Renewable energy replaces conventional fuels in four distinct areas: power generation, hot water/space heating, transport fuels, and rural (off-grid) energy services. Airflows can be used to run wind turbines. Energy in water can be harnessed and used. Since water is about 800 times denser than air, even a slow flowing stream of water or moderate sea swell can yield considerable amount of energy. Solar energy is the energy derived from the sun in the form of solar radiation. Solar-powered electrical generation relies on photovoltaics and heat engines. Solar technologies are broadly characterised as either passive solar or active solar depending on the way they capture, convert and distribute solar energy. Active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. Biomass (plant material) is a renewable energy source because the energy it contains comes from the sun. Through the process of photosynthesis, plants capture the sun's energy. When the plants are burnt, they release the sun's energy they contain. In this way, biomass functions as a sort of natural battery for storing solar energy. As long as biomass is produced sustainably, with only as much used as is grown, the battery will last indefinitely. Biofuels include a wide range of fuels which are derived from biomass. The term covers solid biomass, liquid fuels and various biogases. Liquid biofuels include bioalcohols, such as bioethanol, and oils, such as biodiesel. Gaseous biofuels include biogas, landfill gas and synthetic gas. Geothermal energy is energy obtained by trapping the heat of the earth itself, both from kilometres deep into the earth's crust in volcanically active locations of the globe or from shallow depths, as in geothermal heat pumps in most locations of the planet. It is expensive to build a power station but operating costs are low resulting in low energy costs for suitable sites. Ultimately, this energy derives from heat in the earth's core.

This book on renewable energy sources summarises the various aspects of renewable energy and is divided into 26 chapters.

Chapter 1 is devoted to energy resources and their utilisation. The chapter gives brief outline of non-conventional resources along with India's and world energy resources. Chapter 2 deals with solar radiations which are becoming increasingly appreciated because of their influence on living matter and the feasibility of their application for useful purposes. Chapter 3 concentrates on solar devices such as solar photovoltaic modules, silicon solar cells, solar lanterns, solar lights, solar water pumps and heaters, etc. Chapter 4 focuses on solar thermal energy which can be utilised through two routes—solar thermal route and solar photovoltaic route. Chapter 5 acquaints the readers with solar photovoltaic systems which convert sunlight directly into electricity without creating any air or water pollution. Chapter 6 is devoted to energy-consuming and -converting equipments. Nanotechnology has the potential for significant impact at all stages of the energy value chain. Considering this, Chapter 7 focuses on nanotechnology and solar power. Chapter 8 deals with wind energy which is a form of solar energy and caused by the uneven heating of atmosphere by sun, the irregularities of the earth's surface and rotation of earth. Chapter 9 acquaints the readers with status of wind power in India. Chapter 10 discusses hydroelectric power which comes from flowing water. Water, when it is falling by force of gravity, can be used to turn turbines and generators produce heat. Chapter 11 is devoted to small hydroelectric power on a scale serving a small community or industrial plant. Chapter 12 acquaints the readers with hydropower development in India. Chapter 13 concentrates on tide, wave and ocean energy. These are the form of hydropower that converts the energy of tides into useful forms of power—mainly electricity. Chapter 14 focuses on geothermal power generation which means energy or power extracted from beneath the earth. Geothermal energy is called renewable source of energy because heat is continuously produced inside the earth. Chapter 15 acquaints the readers with geothermal energy resources and its potential in India. Chapter 16 is devoted to biofuels: a review. Biofuels are the types of fuels whose energy is derived from biological carbon fixation. Biofuels include fuels derived from biomass conversion as well as solid biomass, liquid fuels and various biogases. Chapter 17 concentrates on biogas which refers to gas produced by biological breakdown or organic matter in the absence of oxygen. Chapter 18 discusses biomass gasification which is incomplete combustion of biomass resulting in production of combustible gases such as producer gas, hydrogen, traces of methane, etc. Chapter 19 deals with cogeneration of power and low-pressure stream by way of expansion through a turbine.

Chapter 20 is devoted to photosynthesis which is a chemical process that converts carbon dioxide into organic compounds, especially sugars, using energy from sunlight. Chapter 21 concentrates on ethanol which is most often used as a motor fuel in the United States and Brazil. Chapter 22 focuses on biodiesel which refers to a vegetable-oil- or animal-fat-based diesel fuel consisting of long-chain alkyl esters. Chapter 23 deals with biohydrogen which is produced biologically, most commonly by algae and bacteria. Biohydrogen is a potential biofuel obtainable from both cultivation and waste organic materials. Chapter 24 is devoted to algae fuel for future. Chapter 25 deals with nanotech biofuels and fuels additives. Chapter 26 discusses issues related to biofuels which include the effect of moderating oil prices, the 'food vs. fuel debate', carbon emission levels, deforestation and soil erosion.

Such wide coverage makes this book a treatise on the subject. Glossary, references and index have been provided at the end for quick reference. Diagrams, figures, tables and index supplement the text. All the topics have been covered in a cogent and lucid style to help the reader grasp the information quickly and easily.

It will not be wrong to hold that this book on renewable energy sources is essential reading for all students pursuing B. Tech (Civil/Chemical/Mechanical/Environmental Engineering). Besides students, the book is useful to consultants, industrialists and researchers in these and allied fields.

The book also caters to the requirement of the syllabus prescribed by various Indian universities for undergraduate student pursuing undergraduate courses in engineering. It has been prepared with meticulous care, aiming at making the book error-free. Constructive suggestions are always welcome from users of this book.

**S. C. Bhatia**

# 1

# Energy resources and their utilisation

## 1.1 Introduction

Renewable energy is energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). About 16 per cent of global final energy consumption comes from renewables, with 10 per cent coming from traditional biomass, which is mainly used for heating, and 3.4 per cent from hydroelectricity. New renewables (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.8 per cent and are growing very rapidly. The share of renewables in electricity generation is around 19 per cent, with 16 per cent of global electricity coming from hydroelectricity and 3 per cent from new renewables.

While many renewable energy projects are large-scale, renewable technologies are also suited to rural and remote areas, where energy is often crucial in human development. As of 2011, small solar PV systems provide electricity to a few million households, and micro-hydro configured into mini-grids serves many more. Over 44 million households use biogas made in household-scale digesters for lighting and/or cooking, and more than 166 million households rely on a new generation of more-efficient biomass cookstoves.

Climate change concerns, coupled with high oil prices, peak oil, and increasing government support, are driving increasing renewable energy legislation, incentives and commercialisation. New government spending, regulation and policies helped the industry weather the global financial crisis better than many other sectors. According to a 2011 projection by the International Energy Agency, solar power generators may produce most of the world's electricity within 50 years, dramatically reducing the emissions of greenhouse gases that harm the environment.

## 1.2 India's energy resources

India's need to increase energy provision for its population and fast growing economy poses a formidable challenge which is perceived as both a great opportunity as well as a necessity for the country to increase the share of renewables in the overall energy mix. India has been making continuous progress in conventional as well as renewable power generation. India's approach is to meet its energy needs in a responsible, sustainable and ecofriendly manner.

The country has made a remarkable growth in last 2–3 years in the field of renewable energy power generation. The past few years saw a record addition of 2332 MW of renewable energy sources i.e. solar, wind, biomass, geothermal and hydro, etc. which could make important contributions to sustainable development. All these development have taken place in 11th plan period. The bulk addition is in wind generation at 1565 MW, small hydro power segment recorded an addition of 305 MW, cogeneration 295 MW and biomass 153 MW. The lowest additions were in the solar at 8 MW and waste-to-energy segments at 4.7 MW. A target of 14,000 MW capacity addition has been set for the 11th Plan (2007–08 to 2011–12).

The need for renewable energy arises as energy Security is important to our country. As per World Energy Outlook report, India will become the third largest net importer of oil before 2025 after the United States and China. This will not be sustainable in the long run given the high volatility of international crude oil prices. Coal imports are also likely to increase from 12 per cent in 2005 to 28 per cent in 2030. In order to insulate itself from any future supply disruption and price shocks of fossil fuels and furthermore to achieve energy security and also meet global climate change objectives, renewables are a must and has indeed caught the imagination of India.

Riding on the crest of a high growth trajectory and in pursuit of sustainable sources to meet its rising domestic energy demand and access to energy for overall development, the country is focusing on harnessing renewable energy production through maximising the utilisation of renewable energy.

Currently, their exploitation in commercial markets is low, being constrained by costs and uncompensated benefits, as well as intermittent supplies and other technical and institutional considerations. But they have hold on social consideration for:

1. Enhanced energy security by providing supplies that are abundant, diverse and indigenous.
2. Reduced global and local atmospheric emissions when used in place of fossil fuels.
3. Improved options in rural areas and in newly industrialising and developing countries.
4. Increased local and regional employment opportunities in energy infrastructure manufacturing, installation and maintenance for developed and developing countries.

## 1.3 Renewable energy sources

Conventionally, natural resources, like, wind, solar and hydro are termed as renewable energy sources. These terms can be easily understood. Bioenergy, which is another important renewable energy source covers a wide spectrum of energy activities from direct production heat through combustion of fuel wood and other biomass residues, to the generation of electricity and the production of gases and liquid fuel and chemicals. It is widely used globally. The geothermal resources are the internal heat of the earth. Its use covers a range of option from power generation to space heating and/or air conditioning.

### 1.3.1 Growth of renewable power in India

The renewable energy potential in India is as below:

1. Wind power 48,000 MW
2. Small hydro 15,000 MW
3. Biomass power 16,700 MW
4. Bagasse cogeneration 5000 MW
5. Solar energy 20 MW/sq. km
6. Waste to energy 3800 MW

India has been making continuous progress in conventional as well as renewable power generation. The trajectory of growth of installed capacity since year 2002 (start of 10th Plan), 2007 (start of 11th Plan), and at present as on 30-9-2010, is given in Table 1.1.

It may be observed that renewable grid capacity has increased more than 5 times, from 2 per cent to around 11 per cent in only 8 years.

**Table 1.1** Source-wise contribution to installed power generation capacity (MW).

| Time period | Thermal (%) | Hydro (>25 MW) (%) | Nuclear (%) | Renewable power (%) |
|---|---|---|---|---|
| 1-4-2002 | 59% (74429) | 26% (26, 269) | 2% (2720) | 2% (1628) |
| 31-9-2007 | 65% (87015) | 26% (34, 654) | 3% (3900) | 6% (10, 258) |
| 1-4-2010 | 64% (106518) | 22.4% (37, 328) | 2.7% (4560) | 10.90% (18, 155) |

*Total installed capacity:* India's total installed capacity of electricity generation has expanded from 1,05,046 MW at the end of 2,00,102 to 1,66,561 MW at the end of September, 2010. In fact, India ranks sixth globally in terms of total electricity generation.

*Thermal power:* 64.0 per cent of the total installed capacity, producing 1,06,518 MW.

*Hydel power:* Hydel power plants come next with 22.4 per cent of the total an installed capacity of 37,328 MW.

*Renewable energy:* Renewable energy sources contribute around 10.9 per cent to the total power generation in the country producing 18,155 MW (as on 31.9.2010).

## 1.4 Renewable energy capacity in India

All sectors of renewable energy are being developed and promoted. However, the wind power program has been the fastest growing contributing to around 75 per cent of the grid-connected renewable energy power installed capacity.

*Wind power:* Wind power has seen a phenomenal growth of around 33 per cent CAGR (compound annual growth rate) in the last 5 years and the total capacity at end of 2010 was 12129 MW (as on 31-7-2010) with most of the capacity installed in the state of Tamil Nadu in India.

*Solar energy:* Among various renewable energy resources, India possesses a very large solar energy resource which is seen as having the highest potential for the future. The first, recently announced, very ambitious Jawaharlal Nehru National Solar Mission with a target of 20,000 MW grid solar power, 2000 MW of off-grid capacity including 20 million solar lighting systems and 20 million sq. m. solar thermal collector area by 2022 is under implementation, likely to be implemented in three phases. The first phase will be of three years (up to March, 2013), the second till March 2017 and the third phase will continue till March 2022. The target for phase-I is to set up 1100 MW grid connected solar plants including 100 MW of roof top and small solar plants and 200 MW capacity equivalent off-grid solar applications and 7 million sq.m. solar thermal collector area. The main objectives of the mission are to help reach grid parity by 2022 and help set up indigenous manufacturing capacity.

Mini hydro plants: Mini hydro plants are supposed to have a 15 GW potential out of which 2.5 GW has been realised.

*Biomass energy:* Biomass energy has 25 GW of potential out of which around 2.1 GW has been realised.

Rural electrification to meet unmet demand through renewable energy is a priority by itself. 150 villages have been covered in last 2 years through mini grid by rice-husk based gasification systems in Bihar. There are plans to cover about 10,000 villages from biomass-based systems and over 1000 villages from solar power by 2022.

The grid interactive projects (up to 2 MW) at the tail end of the grid at 11 kV to reduce the transmission and distribution losses and stabilise grid voltages are now being piloted. So far, about 112 MW equivalent biomass gasifier systems have been set up in industries for captive power and thermal applications.

## 1.5 Renewables and the environment

Renewable energy is usually more environmental friendly than alternative energy sources. Life-cycle emissions from renewable energy use are small compared with those from fossil fuel plants. Nuclear power generation does have a major environmental impact, it releases no sulphur dioxide ($SO_2$) or nitrogen oxides ($NO_x$) and little carbon dioxide ($CO_2$). Its life-cycle emissions of these gases fall within the ranges shown for non-hydroelectric renewable energy.

Renewable energy entails a number of other potential environmental impacts. On the negative side, renewable energy can make large tracts of land unusable for competing uses, disrupt marine life, bird life and flora/fauna, and produce visual and noise pollution. Generally though, these potential environmental impacts are site-specific and there are a number of ways to minimise the effects, which are usually small and reversible. There are environmental benefits from renewable other than reduction of greenhouse gas and other air emissions. For example, hydroelectric schemes can improve water supplies and facilitate reclamation of degraded land and habitat.

The use of bioenergy can have many environmental benefits if the resource is produced and used in a sustainable way. If the land from which bioenergy is produced is replanted, bioenergy is used sustainably and the carbon released will be recycled into the next generation of growing plants. Bioenergy plants have lower emissions of $SO_2$ than coal and oil plants, but they may produce more particulate matter. These emissions are controllable but they increase generating costs.

The environmental and social effects of large-scale hydropower are site specific and are the subject of much controversy. Large-scale projects may disturb local ecosystems, reduce biological diversity or modify water quality. They may also cause socio-economic damage by displacing local populations. Mini- and micro-hydro systems have relatively modest and localised effects on the environment, but their kWh cost is generally higher. Hydropower emits some greenhouse gases on a life-cycle basis (especially methane generated by decaying bioenergy in reservoirs), but in most cases far less than the burning of fossil fuels.

*Geothermal plants* may release gaseous emissions into the atmosphere during their operation. These gases are mainly carbon dioxide and hydrogen sulphide with traces of ammonia, hydrogen, nitrogen, methane, radon, and the volatile species of boron, arsenic and mercury. This could slow the future development of geothermal resources. Emissions can be managed through strict regulations and by control methods used by the geothermal industry to meet these regulatory requirements. Hydrogen sulphide abatement systems reduce environmental damage but are costly to install.

*Wind-power* generation has very low emissions on a life-cycle basis, but has a number of environmental effects that may limit its potential. The most important effects on the environment are:

1. Visual effects: Wind turbines must be in exposed areas and are therefore highly visible. They are considered unsightly by some people, and concerns have increased with the larger size of new generation turbines.
2. Noise: Wind turbines produce aerodynamic noise, from air passing over the blades and mechanical noise from the moving parts of the turbine, especially the gearbox. Better designs have reduced noise, and research continues. Wind farms developed far from highly populated areas are, by definition, less offensive.
3. Electromagnetic interference: Wind turbines may scatter electromagnetic signals causing interference to communication systems. Appropriate siting (avoiding military zones or airports) can minimise this impact.
4. Bird safety: Birds get killed when they collide with the rotating blades of a turbine. Migratory species are at higher risk than resident species. Siting the turbines away from migratory routes reduces the impact.

## 1.6 Renewable potential vs installed capacity in India

A report of MNRE, shows the total potential of renewable energy that could be harnessed in the country. Table 1.2 shows the break-up of the potentials of different sources.

**Table 1.2** Renewable potential and installed capacity.

| Source | Potential (MW) | Installed capacity (MW) (June 2010 as per MNRE) |
|---|---|---|
| Wind | 45,195 | 12,009.00 |
| Biomass | 16,881 | 901.10 |
| Small hydro | 15,000 | 2767.00 |
| Bagasse-based cogeneration | 5000 | 1412.00 |
| Waste-to-energy | 2700 | 72.46 |
| Solar | 50 MW/sq. km | 12.00 |
| Total | | 17,174.00 |

## 1.7 Total generation installed capacity in India

Table 1.3 shows the generation installed capacity as on June 2010.

**Table 1.3** Installed capacity.

| Fuel | Capacity (MW) | Share (%) |
|---|---|---|
| Thermal | 1,05,646.98 | 64.26 |
| Coal and Lignite | 87093.85 | 52.97 |
| Gas | 17353.85 | 10.55 |
| Diesel and liquid fuels | 1199.75 | 0.73 |
| Hydro | 37033.40 | 22.52 |
| Renewable | 17173.90 | 10.45 |
| Wind | 12009.48 | 7.30 |
| Biomass | 901.10 | 1.68 |
| Small hydro | 2767.05 | 0.55 |
| Bagasse-based cogeneration | 1411.53 | 0.86 |
| Waste-to-energy | 72.46 | 0.04 |
| Solar | 12.38 | 0.01 |
| Nuclear | 4560.00 | 2.77 |
| Total | 164414.28 | 100 |

## 1.8 World energy resources and consumption

World energy consumption in 2010: Over 5 per cent growth energy markets have combined crisis recovery and strong industry dynamism. Energy consumption in the G20 soared by more than 5 per cent in 2010, after the slight decrease of 2009. This strong increase is the result of two converging trends. On the one-hand, industrialised countries, which experienced sharp decreases in energy demand in 2009, recovered firmly in 2010, almost coming back to historical trends. Oil, gas, coal, and electricity markets followed the same trend. On the other hand, China and India, which showed no signs of slowing down in 2009, continued their intense demand for all forms of energy.

In 2009, world energy consumption decreased for the first time in 30 years (–1.1 per cent) or 130 Mtoe (Megaton oil equivalent), as a result of the financial and economic crisis (GDP drop by 0.6 per cent in 2009). This evolution is the result of two contrasting trends. Energy consumption growth remained vigorous in several developing countries, specifically in Asia (+4 per cent). Conversely, in OECD, consumption was severely cut by 4.7 per cent in 2009 and was thus almost down to its 2000 levels. In North America, Europe and Commonwealth of Independent States (CIS), consumptions shrank by 4.5 per cent, 5 per cent and 8.5 per cent respectively due to the slowdown in economic activity. China became the world's largest energy consumer (18 per cent of the total) since its consumption surged by 8 per cent during 2009 (up from 4 per cent in 2008). Oil remained the largest energy source (33 per cent) despite the fact that its share has been decreasing over time. Coal posted a growing role in the world's energy consumption in 2009, it accounted for 27 per cent of the total.

In 2008, total worldwide energy consumption was 474 exajoules ($474 \times 10^{18}$ J = 1,32,000 TWh). This is equivalent to an average energy consumption rate of 15 terawatts ($1.504 \times 10^{13}$ W). The potential for renewable energy is: solar energy 1600 EJ (4,44,000 TWh), wind power 600 EJ (1,67,000 TWh), geothermal energy 500 EJ (1,39,000 TWh), biomass 250 EJ (70,000 TWh), hydropower 50 EJ (14,000 TWh) and ocean energy 1 EJ (280 TWh).

More than half of the energy has been consumed in the last two decades since the industrial revolution, despite advances in efficiency and sustainability. According to IEA world statistics in four years (2004–2008) the world population increased 5 per cent, annual $CO_2$ emissions increased 10 per cent and gross energy production increased 10 per cent. Most energy is used in the country of origin, since it is cheaper to transport final products than raw materials. In 2008 the share export of the total energy production by fuel was: oil 50 per cent (1952/3941 MT), gas 25 per cent (800/3149 bcm), hard coal 14 per cent (793/5845 MT) and electricity 1 per cent (269/20,181 TWh).

Most of the world's energy resources are from the sun's rays hitting earth. Some of that energy has been preserved as fossil energy, some is directly or indirectly usable; for example, via wind, hydro- or wave power. The term solar constant is the amount of incoming solar electromagnetic radiation per unit area, measured on the outer surface of earth's atmosphere, in a plane perpendicular to the rays. The solar constant includes all types of solar radiation, not just visible light. It is measured by satellite to be roughly 1366 watts per square meter, though it fluctuates by about 6.9 per cent during a year—from 1412 $Wm^{-2}$ in early January to 1321 $Wm^{-2}$ in early July, due to the earth's varying distance from the sun, and by a few parts per thousand from day-to-day. For the whole earth, with a cross section of 12,74,00,000 $km^2$, the total energy rate is 174 petawatts ($1.740 \times 10^{17}$ W), plus or minus 3.5 per cent. This value is the total rate of solar energy received by the planet; about half, 89 PW, reaches the earth's surface.

The estimates of remaining non-renewable worldwide energy resources vary, with the remaining fossil fuels totalling an estimated 0.4 YJ (1 YJ = 1024 J) and the available nuclear fuel such as uranium exceeding 2.5 YJ. Fossil fuels range from 0.6 to 3 YJ if estimates of reserves of methane clathrates are accurate and become technically extractable. The total energy flux from the sun is 3.8 YJ/year, dwarfing all non-renewable resources.

From 1990 to 2008 the average use of energy per person as IEA data increased 10 per cent and the world population increased 27 per cent. Regional energy use grew from 1990 to 2008: Middle East 170 per cent, China 146 per cent, India 91 per cent, Africa 70 per cent, Latin America 66 per cent, USA 20 per cent, EU-27 7 per cent and world 39 per cent.

## 1.9 Consumption of energy

### 1.9.1 Primary energy

The United States Energy Information Administration regularly publishes a report on world consumption for most types of primary energy resources.

| Fuel type | Average power in TW | | |
|---|---|---|---|
| | 1980 | 2004 | 2007 |
| Oil | 4.38 | 5.58 | 5.74 |
| Gas | 1.80 | 3.45 | 3.61 |
| Coal | 2.34 | 3.87 | 4.27 |
| Hydroelectric | 0.60 | 0.93 | 1.00 |
| Nuclear power | 0.25 | 0.91 | 0.93 |
| Geothermal, wind, solar energy, wood | 0.02 | 0.13 | 0.16 |
| Total | 9.48 | 15.0 | 15.8 |

### 1.9.2 Renewable energy

Renewable energy comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). As of 2010, about 16 per cent of global final energy consumption comes from renewables, with 10 per cent coming from traditional biomass, which is mainly used for heating, and 3.4 per cent from hydroelectricity. New renewables (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.8 per cent and are growing very rapidly. The share of renewables in electricity generation is around 19 per cent, with

16 per cent of global electricity coming from hydroelectricity and 3 per cent from new renewables.

### 1.9.3 Hydropower

Worldwide hydroelectricity installed capacity reached 816 GW in 2005, consisting of 750 GW of large plants, and 66 GW of small hydro installations. Large hydro capacity totalling 10.9 GW was added by China, Brazil, and India during the year, but there was a much faster growth (8 per cent) small hydro, with 5 GW added, mostly in China where some 58 per cent of the world's small hydro plants are now located. China is the largest hydropower producer in the world, and continues to add capacity. In the Western world, although Canada is the largest producer of hydroelectricity in the world, the construction of large hydro plants has stagnated due to environmental concerns.

The trend in both Canada and the United States has been to micro hydro because it has negligible environmental impacts and opens up many more locations for power generation. In British Columbia alone, the estimates are that micro hydro will be able to more than double electricity production in the province.

### 1.9.4 Biomass and biofuels

Until the beginning of the nineteenth century biomass was the predominant fuel, today it has only a small share of the overall energy supply. Electricity produced from biomass sources was estimated at 44 GW for 2005. Biomass electricity generation increased by over 100 per cent in Germany, Hungary, the Netherlands, Poland, and Spain. A further 220 GW was used for heating (in 2006), bringing the total energy consumed from biomass to around 264 GW. The use of biomass fires for cooking is excluded.

World production of bioethanol increased by 8 per cent in 2007 to reach 33 billion litres (8.72 billion US gallons), with most of the increase in the United States, bringing it level to the levels of consumption in Brazil. Biodiesel increased by 85 per cent to 3.9 billion litres (1.03 billion US gallons), making it the fastest growing renewable energy source in 2007. Over 50 per cent is produced in Germany.

### 1.9.5 Wind power

Wind power is growing at the rate of 30 per cent annually, with a worldwide installed capacity of 198 gigawatts (GW) in 2010, and is widely used in

Europe, Asia, and the United States. Wind power accounts for approximately 19 per cent of electricity use in Denmark, 9 per cent in Spain and Portugal, and 6 per cent in Germany and the Republic of Ireland. The United States is an important growth area and installed US wind power capacity reached 25,170 MW at the end of 2008.

### 1.9.6 Solar power

The available solar energy resources are 3.8 YJ/year (1,20,000 TW). Less than 0.02 per cent of available resources are sufficient to entirely replace fossil fuels and nuclear power as an energy source. Assuming that our rate of usage in 2007 remains constant, estimated reserves are accurate, and no new unplanned reserves are found, we will run out of conventional oil in 2045, and coal in 2159. In practice, neither will actually run out as natural constraints will force production to decline as the remaining reserves dwindle. The rate at which demand increases and reserves dwindle has been increasing dramatically because the rate of consumption is not constant. For example, if demand for oil doubled, reserves would not last as long. In addition, the cost of fossil fuels continues to rise while solar power becomes more economically viable.

In 2007 grid-connected photovoltaic electricity was the fastest growing energy source, with installations of all photovoltaics increasing by 83 per cent in 2009 to bring the total installed capacity to 15 GW. Nearly half of the increase was in Germany, which is now the world's largest consumer of photovoltaic electricity (followed by Japan). Solar cell production increased by 50 per cent in 2007, to 3800 MW, and has been doubling every two years.

The consumption of solar hot water and solar space heating was estimated at 88 GW (gigawatts of thermal power) in 2006. The heating of water for unglazed swimming pools is excluded.

### 1.9.7 Geothermal

Geothermal energy is used commercially in over 70 countries. In the year 2006, 200 PJ (57 TWh) of electricity was generated from geothermal resources, and an additional 270 PJ of geothermal energy was used directly, mostly for space heating. In 2007, the world had a global capacity for 10 GW of electricity generation and an additional 28 GW of direct heating, including extraction by geothermal heat pumps. Heat pumps are small and widely distributed, so estimates of their total capacity are uncertain and range up to 100 GW.

### 1.9.8 Consumption by country

Energy consumption is loosely correlated with gross national product and climate, but there is a large difference even between the most highly developed countries, such as Japan and Germany with 6 kWh per person and United States with 11.4 kWh per person. In developing countries, particularly those that are subtropical or tropical such as India, the per person energy use is closer to 0.7 kWh. Bangladesh has the lowest consumption with 0.2 kWh per person.

The US consumes 25 per cent of the world's energy with a share of global GDP at 22 per cent and a share of the world population at 4.59 per cent. The most significant growth of energy consumption is currently taking place in China, which has been growing at 5.5 per cent per year over the last 25 years. Its population of 1.3 billion people (19.6 per cent of the world population) is consuming energy at a rate of 1.6 kWh per person.

One measurement of efficiency is energy intensity. This is a measure of the amount of energy it takes a country to produce a dollar of gross domestic product.

### 1.9.9 Consumption by sector

Industrial users (agriculture, mining, manufacturing, and construction) consume about 37 per cent of the total 15 TW. Personal and commercial transportation consumes 20 per cent; residential heating, lighting, and appliances use 11 per cent; and commercial uses (lighting, heating and cooling of commercial buildings, and provision of water and sewer services) amount to 5 per cent of the total.

The other 27 per cent of the world's energy is lost in energy transmission and generation. In 2007, global electricity consumption averaged 2 TW. The energy rate used to generate 2 TW of electricity is approximately 5 TW, as the efficiency of a typical existing power plant is around 38 per cent. The new generation of gas-fired plants reaches a substantially higher efficiency of 55 per cent. Coal is the most common fuel for the world's electricity plants.

Total world energy use per sector was in 2008 industry 28 per cent, transport 27 per cent and residential and service 36 per cent.

## 1.10 Renewable resources

Renewable resources are available each year, unlike non-renewable resources, which are eventually depleted. A simple comparison is a coal mine and a forest. While the forest could be depleted, if it is managed it represents a continuous supply of energy, vs. the coal mine, which once has been exhausted is gone. Most of earth's available energy resources are renewable resources. Renewable resources account for more than 93 per cent of total US energy reserves. Annual renewable resources were multiplied times thirty years for comparison with non-renewable resources. In other words, if all non-renewable resources were uniformly exhausted in 30 years, they would only account for 7 per cent of available resources each year, if all available renewable resources were developed.

### 1.10.1 Solar energy

Renewable energy sources are even larger than the traditional fossil fuels and in theory can easily supply the world's energy needs. 89 PW of solar power falls on the planet's surface. While it is not possible to capture all, or even most, of this energy, capturing less than 0.02 per cent would be enough to meet the current energy needs. Barriers to further solar generation include the high price of making solar cells and reliance on weather patterns to generate electricity. Also, current solar generation does not produce electricity at night, which is a particular problem in high northern and southern latitude countries; energy demand is highest in winter, while availability of solar energy is lowest. This could be overcome by buying power from countries closer to the equator during winter months, and may also be addressed with technological developments like Infrared Solar Panel systems, which can capture energy in cloudy conditions and even at night. Globally, solar generation is the fastest growing source of energy, seeing an annual average growth of 35 per cent over the past few years. Japan, Europe, China, US and India are the major growing investors in solar energy.

### 1.10.2 Wind power

The available wind energy estimates range from 300 TW to 870 TW. Using the lower estimate, just 5 per cent of the available wind energy would supply the current worldwide energy needs. Most of this wind energy is available over the open ocean. The oceans cover 71 per cent of the planet and wind tends to blow more strongly over open water because there are fewer obstructions.

### 1.10.3 Wave and tidal power

At the end of 2006, 0.3 GW of electricity was produced by tidal power. Due to the tidal forces created by the moon (68 per cent) and the sun (32 per cent), and the earth's relative rotation with respect to moon and sun, there are fluctuating tides. These tidal fluctuations result in dissipation at an average rate of about 3.7 TW.

Another physical limitation is the energy available in the tidal fluctuations of the oceans, which is about 0.6 EJ (exajoule). Note this is only a tiny fraction of the total rotational energy of the earth. Without forcing, this energy would be dissipated (at a dissipation rate of 3.7 TW) in about four semi-diurnal tide periods. So, dissipation plays a significant role in the tidal dynamics of the oceans. Therefore, this limits the available tidal energy to around 0.8 TW (20 per cent of the dissipation rate) in order not to disturb the tidal dynamics too much. Waves are derived from wind, which is in turn derived from solar energy, and at each conversion there is a drop of about two orders of magnitude in available energy. The total power of waves that wash against our shores add up to 3 TW.

### 1.10.4 Geothermal

Estimates of exploitable worldwide geothermal energy resources vary considerably, depending on assumed investments in technology and exploration and guesses about geological formations. According to a 2007 study, it was thought that this might amount to between 65 and 138 GW of electrical generation capacity 'using enhanced technology'. Other estimates range from 35 to 2000 GW of electrical generation capacity, with a further potential for 140 EJ/year of direct use.

A 2006 report by MIT that took into account the use of enhanced geothermal systems (EGS) concluded that it would be affordable to generate 100 GWe (gigawatts of electricity) or more by 2050, just in the United States, for a maximum investment of 1 billion US dollars in research and development over 15 years. The MIT report calculated the world's total EGS resources to be over 13 YJ, of which over 200 ZJ would be extractable, with the potential to increase this to over 2 YJ with technology improvements—sufficient to provide all the world's energy needs for several millennia. The total heat content of the earth is 1,30,00,000 YJ.

### 1.10.5 Biomass

Production of biomass and biofuels are growing industries as interest in sustainable fuel sources is growing. Utilising waste products avoids a food vs. fuel trade-off, and burning methane gas reduces greenhouse gas emissions, because even though it releases carbon dioxide, carbon dioxide is 23 times less of a greenhouse gas than is methane. Biofuels represent a sustainable partial replacement for fossil fuels, but their net impact on greenhouse gas emissions depends on the agricultural practices used to grow the plants used as feedstock to create the fuels. While it is widely believed that biofuels can be carbon-neutral, there is evidence that biofuels produced by current farming methods are substantial net carbon emitters. Geothermal and biomass are the only two renewable energy sources that require careful management to avoid local depletion.

### 1.10.6 Hydropower

In 2006, hydroelectric power supplied 16.4 per cent of world electricity, down from 21.0 per cent in 1973, but only 2.2 per cent of the world's energy.

### 1.10.7 Alternative energy paths

Denmark and Germany have started to make investments in solar energy, despite their unfavourable geographic locations. Germany is now the largest consumer of photovoltaic cells in the world. Denmark and Germany have installed 3 GW and 17 GW of wind power respectively. In 2006, wind generated 18.5 per cent of all the electricity in Denmark. Brazil invests in ethanol production from sugar cane, which is now a significant part of the transportation fuel in that country. Starting in 1965, France made large investments in nuclear power and to this date three quarters of its electricity comes from nuclear reactors. Switzerland is planning to cut its energy consumption by more than half to become a 2000-watt society by 2050 and the United Kingdom is working towards a zero energy building standard for all new housing by 2016.

## 1.11 Energy planning

Energy planning has a number of different meanings. However, one common meaning of the term is the process of developing long-range policies to help guide the future of a local, national, regional or even the global energy system. Energy planning is often conducted within governmental organisations but may also be carried out by large energy companies such as electric utilities or oil and gas producers. Energy planning may be carried out with input from different stakeholders drawn from government agencies, local utilities, academia and other interest groups. Energy planning is often conducted using integrated approaches that consider both the provision of energy supplies and the role of energy efficiency in reducing demands. Energy planning should always reflect the outcomes of population growth.

Energy planning has traditionally played a strong role in setting the framework for regulations in the energy sector (for example, influencing what type of power plants might be built or what prices were charged for fuels). But in the past two decades many countries have deregulated their energy systems so that the role of energy planning has been reduced, and decisions have increasingly been left to the market. This has arguably led to increased competition in the energy sector, although there is little evidence that this has translated into lower energy prices for consumers. Indeed in some cases, deregulation has led to significant concentrations of 'market power' with large very profitable companies having a large influence as price setters.

This trend now seems to be reversing as concerns grow over the environmental impacts of energy consumption and production, particularly in light of the threat of global climate change, which is caused largely by emissions of greenhouse gases from the world's energy systems.

Sustainable energy planning is particularly appropriate for communities who want to develop their own energy security, while employing best available practice in their planning processes.

## 1.12 Energy intensity

Energy intensity is a measure of the energy efficiency of a nation's economy. It is calculated as units of energy per unit of GDP.

1. High energy intensities indicate a high price or cost of converting energy into GDP.
2. Low energy intensity indicates a lower price or cost of converting energy into GDP.

Energy Intensity as defined here is not to be confused with energy use intensity (EUI), a measure of building energy use per unit area.

Many factors influence an economy's overall energy intensity. It may reflect requirements for general standards of living and weather conditions in an economy. It is not a typical for particularly cold or hot climates to require greater energy consumption in homes and workplaces for heating (furnaces or electric heaters) or cooling (air conditioning, fans, refrigeration). A country with an advanced standard of living is more likely to have a wider prevalence of such consumer goods and thereby be impacted in its energy intensity than one with a lower standard of living. Energy efficiency of appliances and buildings (through use of building materials and methods, such as insulation), fuel economy of vehicles, vehicular distances travelled (frequency of travel or larger geographical distances), better methods and patterns of transportation, capacities and utility of mass transit, energy rationing or conservation efforts, 'off-grid' energy sources, and stochastic economic shocks such as disruptions of energy due to natural disasters, wars, massive power outages, unexpected new sources, efficient uses of energy or energy subsidies may all impact overall energy intensity of a nation.

Thus, a nation that is highly economically productive, with mild and temperate weather, demographic patterns of work places close to home, and uses fuel efficient vehicles, supports carpools, mass transportation or walks or rides bicycles, will have a far lower energy intensity than a nation that is economically unproductive, with extreme weather conditions requiring heating and cooling, long commutes, and extensive use of generally poor fuel economy vehicles. Paradoxically, some activities that may seem to promote high energy intensities, such as long commutes, could in fact result in lower energy intensities by causing a disproportionate increase in GDP output. Figures of energy consumption used in statistics are energy sources marketed through major energy industries. Therefore some small scale but frequent consumption of energy source like firewood, charcoal peat, water wheel, and wind mill are not in its count. The countries that do not have such developed energy industries or people with highly self-energy efficient life style report smaller energy consumption figures. Energy intensity can be used as a comparative measure between countries; whereas the change in energy consumption required to raise GDP in a specific country over time is described as its energy elasticity.

## 1.13 Energy development

Energy development is the effort to provide sufficient primary energy sources and secondary energy forms for supply, cost, impact on air pollution and water pollution, mitigation of climate change with renewable energy.

Technologically advanced societies have become increasingly dependent on external energy sources for transportation, the production of many manufactured goods, and the delivery of energy services. This energy allows people who can afford the cost to live under otherwise unfavourable climatic conditions through the use of heating, ventilation, and/or air conditioning. Level of use of external energy sources differs across societies, as do the climate, convenience, levels of traffic congestion, pollution and availability of domestic energy sources. All terrestrial energy sources except nuclear, geothermal and tidal are from current solar insolation or from fossil remains of plant and animal life that relied directly and indirectly upon sunlight, respectively. Ultimately, solar energy itself is the result of the sun's nuclear fusion. Geothermal power from hot, hardened rock above the magma of the earth's core is the result of the decay of radioactive materials present beneath the earth's crust, and nuclear fission relies on man-made fission of heavy radioactive elements in the earth's crust; in both cases these elements were produced in supernova explosions before the formation of the solar system.

## 1.14 Fossil fuels

Fossil fuels sources burn coal or hydrocarbon fuels, which are the remains of the decomposition of plants and animals. There are three main types of fossil fuels: coal, petroleum, and natural gas. Another fossil fuel, liquefied petroleum gas (LPG), is principally derived from the production of natural gas. Heat from burning fossil fuel is used either directly for space heating and process heating or converted to mechanical energy for vehicles, industrial processes or electrical power generation.

### *Pros*

1. The technology and infrastructure already exist for the use of the fossil fuels.
2. Petroleum energy density in terms of volume (cubic space) and mass (weight) is superior to some alternative energy sources [or energy storage devices, like a battery (electricity)].
3. Fossil fuels are currently more economical, and more suitable for decentralised energy use.

### *Cons*

1. Petroleum-powered vehicles are very inefficient. Only about 30 per cent of the energy from the fuel they consume is converted into mechanical energy. The rest of the fuel-source energy is inefficiently expanded as waste heat. The heat and gaseous pollution emissions harm our environment.
2. The inefficient atmospheric combustion (burning) of fossil fuels in vehicles, buildings, and power plants contributes to urban heat islands.
3. The combustion of fossil fuels leads to the release of pollution into the atmosphere.
4. Dependence on fossil fuels from volatile regions or countries creates energy security risks for dependent countries.
5. Fossil fuels are non-renewable, unsustainable resources, which will eventually decline in production and become exhausted, with dire consequences to societies that remain highly dependent on them.
6. Extraction of fossil fuels results in extensive environmental degradation, such as the strip mining and mountaintop removal of coal.

## 1.14.1 Nuclear energy

### *Nuclear fission*

Nuclear power stations use nuclear fission to generate energy by the reaction of uranium-235 inside a nuclear reactor. The reactor uses uranium rods, the atoms of which are split in the process of fission, releasing a large amount of energy. The process continues as a chain reaction with other nuclei. The energy heats water to create steam, which spins a turbine generator, producing electricity.

## *Nuclear fusion*

Fusion power could solve many of the problems of fission power (the technology mentioned above) but, despite research having started in the 1950s, no commercial fusion reactor is expected before 2050. Many technical problems remain unsolved. Proposed fusion reactors commonly use deuterium, an isotope of hydrogen, as fuel and in most current designs also lithium. Assuming a fusion energy output equal to the current global output and that this does not increase in the future, then the known current lithium reserves would last 3000 years, lithium from sea water would last 60 million years, and a more complicated fusion process using only deuterium from sea water would have fuel for 150 billion years.

## *Fuel cell*

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidising agent. Hydrogen is the most common fuel, but hydrocarbons such as natural gas and alcohols like methanol are sometimes used. Fuel cells are different from batteries in that they require a constant source of fuel and oxygen to run, but they can produce electricity continually for as long as these inputs are supplied.

Welsh Physicist William Grove developed the first crude fuel cells in 1839. The first commercial use of fuel cells was in NASA space programs to generate power for probes, satellites and space capsules. Since then, fuel cells have been used in many other applications. Fuel cells are used for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. They are used to power fuel cell vehicles, including automobiles, buses, forklifts, airplanes, boats, motorcycles and submarines.

There are many types of fuel cells, but they all consist of an anode (negative side), a cathode (positive side) and an electrolyte that allows charges to move between the two sides of the fuel cell. Electrons are drawn from the anode to the cathode through an external circuit, producing direct current electricity. As the main difference among fuel cell types is the electrolyte, fuel cells are classified by the type of electrolyte they use.

Fuel cells come in a variety of sizes. Individual fuel cells produce very small amounts of electricity, about 0.7 volts, so cells are ‘stacked’ or placed in series or parallel circuits, to increase the voltage and current output to meet an application’s power generation requirements. In addition to electricity, fuel cells produce water, heat and, depending on the fuel source, very small amounts of nitrogen dioxide and other emissions. The energy efficiency of a fuel cell is generally between 40–60 per cent or up to 85 per cent efficient if waste heat is captured for use.

Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electric current is created, which can be used to power electrical devices, normally referred to as the load. Figure 1.1 shows a block diagram of a fuel cell.

At the anode a catalyst oxidises the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electric current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

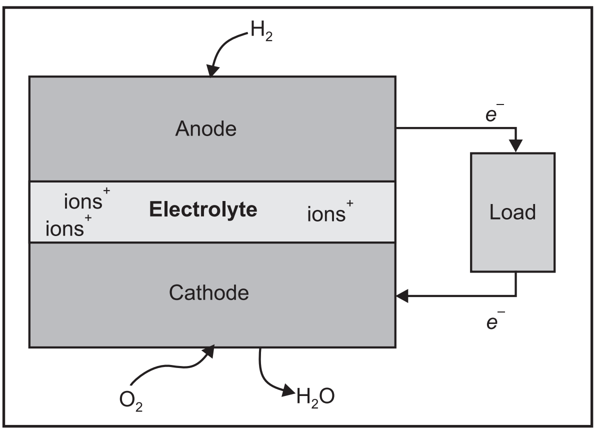



**Figure 1.1** A block diagram of a fuel cell

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. Voltage decreases as current increases, due to several factors:

1. Activation loss.

2. Ohmic loss (voltage drop due to resistance of the cell components and interconnects).
3. Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage).

To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series yields higher voltage, and parallel allows a higher current to be supplied. Such a design is called a fuel cell stack. The cell surface area can be increased, to allow stronger current from each cell.

## 1.15 Renewable sources

Renewable energy is energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). Renewable energy is an alternative to fossil fuels and nuclear power, and was commonly called alternative energy in the 1970s and 1980s.

### 1.15.1 Biomass, biofuels and vegetable oil

Biomass production involves using garbage or other renewable resources such as corn or other vegetation to generate electricity. When garbage decomposes, the methane produced is captured in pipes and later burned to produce electricity. Vegetation and wood can be burned directly to generate energy, like fossil fuels or processed to form alcohols.

Vegetable oil is generated from sunlight, $H_2O$, and $CO_2$ by plants. It is safer to use and store than gasoline or diesel as it has a higher flash point. Straight vegetable oil works in diesel engines if it is heated first. Vegetable oil can also be transesterified to make biodiesel, which burns like normal diesel.

#### *Pros*

1. Biomass production can be used to burn organic by-products resulting from agriculture.
2. Biomass is abundant on earth and is generally renewable. In theory, we will never run. Biomass is found throughout the world, a fact that should alleviate energy pressures in third world nations.
3. When methods of biomass production other than direct combustion of plant mass are used, such as fermentation and pyrolysis, there is little effect on the environment. Alcohols and other fuels produced by these alternative methods are clean burning and are feasible replacements to fossil fuels.

4. Since $CO_2$ is first taken out of the atmosphere to make the vegetable oil and then put back after it is burned in the engine, there is no net increase in $CO_2$.
5. By combining the use of biomass with geo-sequestration of $CO_2$ then this could result in a net decrease of $CO_2$ in the atmosphere.
6. Vegetable oil has a higher flash point and therefore is safer than most fossil fuels.
7. Transitioning to vegetable oil could be relatively easy as biodiesel works where diesel works, and straight vegetable oil takes relatively minor modifications.
8. Infrastructure for biodiesel around the World is significant and growing.

*Cons*

1. Direct combustion of any carbon-based fuel leads to air pollution similar to that from fossil fuels.
2. Direct competition with land use for food production and water use. As this decreases food supply, the price of food increases worldwide.
3. Current production methods would require enormous amounts of land to replace all gasoline and diesel.

### 1.15.2 Geothermal energy

Geothermal energy harnesses the heat energy present underneath the earth. Two wells are drilled. One well injects water into the ground to provide water. The hot rocks heat the water to produce steam. The steam that shoots back up the other hole(s) is purified and is used to drive turbines, which power electric generators. When the water temperature is below the boiling point of water a binary system is used. A low boiling point liquid is used to drive a turbine and generator in a closed system similar to a refrigeration unit running in reverse.

*Pros*

1. Geothermal energy is base load power.
2. Economically feasible in high grade areas now.
3. Low deployment costs.
4. Geothermal power plants have a high capacity factor; they run continuously day and night with an uptime typically exceeding 95 per cent.
5. Once a geothermal power station is implemented, the energy produced from the station is practically free, minus maintenance costs. A small

amount of energy is required in order to run a pump, although this pump can be powered by excess energy generated at the plant.

6. Geothermal power stations are relatively small, and have a lesser impact on the environment than tidal or hydroelectric plants. Because geothermal technology does not rely on large bodies of water, but rather, small, but powerful jets of water, like geysers, large generating stations can be avoided without losing functionality.
7. Geothermal is now feasible in areas where the earth's crust is thicker. Using enhanced geothermal technology, it is possible to drill deeper and to inject water to generate geothermal power.
8. Geothermal energy does not produce air or water pollution if performed correctly.

#### *Cons*

1. Geothermal power extracts small amounts of minerals such as sulphur that are removed prior to feeding the turbine and re-injecting the water back into the injection well.
2. Geothermal power requires locations that have suitable subterranean temperatures within 5 km of surface.
3. Some geothermal stations have created geological instability, even causing earthquakes strong enough to damage buildings.

### 1.15.3 Hydroelectric energy

Energy in water can be harnessed and used. Since water is about 800 times denser than air, even a slow flowing stream of water or moderate sea swell, can yield considerable amounts of energy. In hydro energy, the gravitational descent of a river is compressed from a long run to a single location with a dam or a flume. This creates a location where concentrated pressure and flow can be used to turn turbines or water wheels, which drive a mechanical mill or an electric generator.

#### *Pros*

1. Hydroelectric power stations can promptly increase to full capacity, unlike other types of power stations. This is because water can be accumulated above the dam and released to coincide with peak demand.
2. Electricity can be generated constantly, so long as sufficient water is available.

3. Hydroelectric power produces no primary waste or pollution.
4. Hydropower is a renewable resource.
5. Hydroelectricity assists in securing a country's access to energy supplies.
6. Much hydroelectric capacity is still undeveloped, such as in Africa.

### *Cons*

1. The construction of a dam can have a serious environmental impact on the surrounding areas. The amount and the quality of water downstream can be affected, which affects plant life both aquatic, and land-based. Because a river valley is being flooded, the local habitat of many species is destroyed, while people living nearby may have to relocate their homes.
2. Hydroelectricity can only be used in areas where there is a sufficient and continuing supply of water.
3. Flooding submerges large forests (if they have not been harvested). The resulting anaerobic decomposition of the carboniferous materials releases methane, a greenhouse gas.
4. Dams can contain huge amounts of water. As with every energy storage system, failure of containment can lead to catastrophic results, e.g. flooding.
5. Dams create large lakes that may have adverse effects on earth tectonic system causing intense earthquakes.
6. Hydroelectric plants rarely can be erected near load centers, requiring long transmission lines.

## 1.15.4 Solar power

Solar power involves using solar cells to convert sunlight into electricity, using sunlight hitting solar thermal panels to convert sunlight to heat water or air, using sunlight hitting a parabolic mirror to heat water (producing steam) or using sunlight entering windows for passive solar heating of a building. It would be advantageous to place solar panels in the regions of highest solar radiation.

### *Pros*

1. Solar power imparts no fuel costs.
2. Solar power is a renewable resource. As long as the sun exists, its energy will reach earth.

3. Solar power generation releases no water or air pollution, because there is no combustion of fuels.
4. In sunny countries, solar power can be used in remote locations, like a wind turbine. This way, isolated places can receive electricity, when there is no way to connect to the power lines from a plant.
5. Solar energy can be used very efficiently for heating (solar ovens, solar water and home heaters) and day lighting.
6. Coincidentally, solar energy is abundant in regions that have the largest number of people living off grid—in developing regions of Africa, Indian subcontinent and Latin America. Hence cheap solar, when available, opens the opportunity to enhance global electricity access considerably, and possibly in a relatively short time period.
7. Passive solar building design and zero energy buildings are demonstrating significant energy bill reduction, and some are cost-effectively off the grid.
8. Photovoltaic equipment cost has been steadily falling, the production capacity is rapidly rising.
9. Distributed point-of-use photovoltaic systems eliminate expensive long-distance electric power transmission losses.
10. Photovoltaics are much more efficient in their conversion of solar energy to usable energy than biofuel from plant materials.

### *Cons*

1. Solar electricity is currently more expensive than grid electricity.
2. Solar heat and electricity are not available at night and may be unavailable because of weather conditions; therefore, a storage or complementary power system is required for off-the-grid applications.
3. Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in currently existing distribution grids. This incurs an energy loss of 4–12 per cent.
4. The energy payback time—the time necessary for producing the same amount of energy as needed for building the power device—for photovoltaic cells is about 1–5 years, depending primarily on location.

## 1.15.5 Tidal power generation

Tidal power can be extracted from moon-gravity-powered tides by locating a water turbine in a tidal current or by building impoundment pond dams that admit-or-release water through a turbine. The turbine can turn an electrical generator or a gas compressor, that can then store energy until needed. Coastal tides are a source of clean, free, renewable, and sustainable energy.

### *Pros*

1. Tidal power is free once the dam is built. This is because tidal power harnesses the natural power of tides and does not consume fuel. In addition, the maintenance costs associated with running a tidal station are relatively inexpensive.
2. Tides are very reliable because it is easy to predict when high and low tides will occur. The tide goes in and out twice a day usually at the predicted times. This makes tidal energy easy to maintain, and positive and negative spikes in energy can be managed.
3. Tidal energy is renewable, because nothing is consumed in the rising of tides. Tidal power relies on the gravitational pull of the moon and sun, which pull the sea backwards and forwards, generating tides.

### *Cons*

1. Tidal power is not currently economically feasible, because the initial costs of building a dam are tremendous. Furthermore, it only provides power for around 10 hours each day, when the tide is moving in or out of the basin.
2. The barrage construction can affect the transportation system in water. Boats may not be able to cross the barrage, and commercial ships, used for transport or fishery, need to find alternative routes or costly systems to go through the barrage.
3. The erection of a barrage may affect the aquatic ecosystems surrounding it. The environment affected by the dam is very wide, altering areas numerous miles upstream and downstream. For example, many birds rely on low tides to unearth mud flats, which are used as feeding areas.
4. Maximum energy production is limited to 2.5 terawatts. This is the total amount of tidal dissipation or the friction measured by the slowing of the lunar orbit.

## 1.15.6 Wind power

This type of energy harnesses the power of the wind to propel the blades of wind turbines. These turbines cause the rotation of magnets, which creates electricity. Wind towers are usually built together on wind farms.

### *Pros*

1. Wind power produces no water or air pollution that can contaminate the environment, because there are no chemical processes involved in wind power generation. Hence, there are no waste by-products, such as carbon dioxide.
2. Power from the wind does not contribute to global warming because it does not generate greenhouse gases.
3. Wind generation is a renewable source of energy, which means that we will never run out of it.
4. Wind towers can be beneficial for people living permanently or temporarily, in remote areas. It may be difficult to transport electricity through wires from a power plant to a faraway location and thus, wind towers can be set up at the remote setting.
5. Farming and grazing can still take place on land occupied by wind turbines.
6. Those utilising wind power in a grid-tie configuration will have backup power in the event of a power outage.
7. Because of the ability of wind turbines to coexist within agricultural fields, siting costs are frequently low.

### *Cons*

1. Wind is unpredictable; therefore, wind power is not predictably available. When the wind speed decreases less electricity is generated. This makes wind power unsuitable for base load generation.
2. Wind farms may be challenged in communities that consider them an eyesore or obstruction.
3. Wind farms, depending on the location and type of turbine, may negatively affect bird migration patterns, and may pose a danger to the birds themselves (primarily an issue with older/smaller turbines).
4. Windfarms may interfere with radar creating a hole in radar coverage and so affect national security.
5. Tall wind turbines have been proven to impact Doppler radar towers and affect weather forecasting in a negative way. This can be prevented by not having the wind turbines in the radar's line of sight.

## 1.15.7 Photovoltaics

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulphide. Due to the growing demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years.

Photovoltaics are best known as a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons. The photovoltaic effect refers to photons of light exciting electrons into a higher state of energy, allowing them to act as charge carriers for an electric current. The term photovoltaic denotes the unbiased operating mode of a photodiode in which current through the device is entirely due to the transduced light energy. Virtually all photovoltaic devices are some type of photodiode.

Solar cells produce direct current electricity from sun light, which can be used to power equipment or to recharge a battery. The first practical application of photovoltaics was to power orbiting satellites and other spacecraft, but today the majority of photovoltaic modules are used for grid connected power generation. In this case an inverter is required to convert the DC to AC. There is a smaller market for off-grid power for remote dwellings, boats, recreational vehicles, electric cars, roadside emergency telephones, remote sensing, and cathodic protection of pipelines.

*In buildings:* Photovoltaic arrays are often associated with buildings: either integrated into them, mounted on them or mounted nearby on the ground. Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings as a principal or ancillary source of electrical power.

*In transport:* PV has traditionally been used for electric power in space. PV is rarely used to provide motive power in transport applications, but is being used increasingly to provide auxiliary power in boats and cars.

*Rural electrification:* Unlike the past decade, which saw solar solutions purchased mainly by international donors, it is now the locals who are increasingly opening their wallets to make the switch from their traditional energy means. That is because solar products prices in recent years have declined to become cheaper than kerosene and batteries. Developing countries where many villages are often more than five kilometres away from grid power are increasingly using photovoltaics. In remote locations in India a rural lighting program has been providing solar powered LED lighting to replace kerosene lamps.

## *Advantages and disadvantages of solar photovoltaics*

*Advantages*

Solar power is pollution-free during use. Production end-wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under development and policies are being produced that encourage recycling from producers.

PV installations can operate for many years with little maintenance or intervention after their initial set-up, so after the initial capital cost of building any solar power plant, operating costs are extremely low compared to existing power technologies. As of 2010, the price of PV modules per MW has fallen by 60 per cent since the summer of 2008, according to Bloomberg New Energy Finance estimates, putting solar power for the first time on a competitive footing with the retail price of electricity in a number of sunny countries. There has been fierce competition in the supply chain, and further improvements in the levelised cost of energy for solar lie ahead, posing a growing threat to the dominance of fossil fuel generation sources in the next few years.

When grid-connected, solar electric generation replaces some or all of the highest-cost electricity used during times of peak demand (in most climatic regions). This can reduce grid loading, and can eliminate the need for local battery power to provide for use in times of darkness. These features are enabled by net metering. Time-of-use net metering can be highly favourable, but requires newer electronic metering, which may still be impractical for some users.

*Disadvantages*

Photovoltaics are costly to install. Solar electricity is not produced at night and is greatly reduced in cloudy conditions requiring alternate sources of power. While many buildings with photovoltaic arrays are tied into the power grid which absorbs any excess electricity generated throughout the day and provides electricity in the evening, such systems use a grid tie inverter to convert direct current (DC) alternating current (AC) incurring an energy loss of 4–12 per cent. Off-grid systems use either storage batteries which also incur significant energy losses and require regular maintenance or engine-generators which consume costly fuel.

Solar electricity production depends on the limited power density of the location's insolation. Average daily output of a flat plate collector at latitude tilt in the contiguous US is 3–7 kilowatt·h/m$^2$/day and on average lower in Europe.

Solar electricity is more expensive than most other forms of small-scale alternative energy production. Without governments mandating ‘feed-in-tariffs’ for green solar energy, solar PV is less affordable to homeowners than solar hot water or solar space heating.

Photovoltaic panels are specifically excluded in Europe from RoHS (Restriction on Hazardous Substances) since 2003 and were again excluded in 2011. California has largely adopted the RoHS standard through EWRA. Therefore, PV panels may legally in Europe and California contain lead, mercury and cadmium which are forbidden or restricted in all other electronics. Much of the investment in a home-mounted system may be lost if the homeowner moves and the buyer puts less value on the system than the seller.

## 1.16 Environmental impacts of hydrogen-based energy systems

There is increasing interest in the role that hydrogen-based energy systems may play in the future, especially in the transport sector. They appear to be an attractive alternative to current fossil fuel-based energy systems in the future, since these have been proven to affect climate due to greenhouse gases emissions. Nevertheless, any future hydrogen-based economy would need to assess the possible global environmental impacts of such alternative energy production.

British scientists have recently reviewed current understanding of the fate and behaviour of hydrogen in the atmosphere and characterised its major sources and sinks. They show that, contrary to most expectations, hydrogen is an indirect greenhouse gas with a potential global warming effect. They then quantified the global warming potential of hydrogen in comparison to $CO_2$ and the global warming consequences of replacing the current fossil fuel-based economy with one based on hydrogen.

The results suggest that because hydrogen reacts in the atmosphere with tropospheric OH radicals, the emission of hydrogen into the atmosphere would disrupt the distribution of methane and ozone, the second and third most important greenhouse gases. Emissions of hydrogen lead to increased burdens of methane and ozone and hence to an increase in global warming. Therefore, hydrogen can be considered as an indirect greenhouse gas with the potential to increase global warming.

The scientists have estimated that the potential effects on climate from hydrogen-based energy systems would be much lower than those from fossil fuel-based energy systems. However, such impacts will depend on the rate of hydrogen leakage during its synthesis, storage and use. The researchers have calculated that a global hydrogen economy with a leakage rate of 1 per cent of the produced hydrogen would produce a climate impact of 0.6 per cent of the fossil fuel system it replaces. If the leakage rate was 10 per cent, then the climate impact would be 6 per cent of that of the fossil fuel system.

The current study suggests that a future hydrogen-based economy would not be free from climate disturbance, although this may be considerably less pronounced that caused by the current fossil fuel energy systems. Careful attention would have to be paid to reducing hydrogen leakage to a minimum if the potential climate benefits of a future global hydrogen economy are to be realised.

# 2
# Solar radiations

## 2.1 Introduction

Solar radiations are becoming increasingly appreciated because of their influence on living matter and the feasibility of its application for useful purposes. It is a perpetual source of natural energy that, along with other forms of renewable energy, has a great potential for a wide variety of applications because it is abundant and accessible. Solar radiation is rapidly gaining ground as a supplement to the nonrenewable sources of energy, which have a finite supply. The electromagnetic radiation emitted by the sun covers a very large range of wavelengths, from radiowaves through the infrared, visible and ultraviolet to X-rays and gamma rays. However, 99 per cent of the energy of solar radiation is contained in the wavelength band from 0.15 to 4 μm, comprising the near ultraviolet, visible and near infrared regions of the solar spectrum, with a maximum at about 0.5 μm. About 40 per cent of the solar radiation received at the earth's surface on clear days is visible radiation within the spectral range 0.4 to 0.7 μm, while 51 per cent is infrared radiation in the spectral region 0.7 to 4 μm.

The total radiation emitted by the sun in unit time remains practically constant. The variations actually observed in association with solar phenomena like sunspots, prominences and solar flares are mainly confined to the extreme ultraviolet end of the solar spectrum and to the radiowaves. The contribution of these variations to the total energy emitted is extremely small and can be neglected in solar energy applications. The planet earth revolves around the sun in an elliptical orbit of very small eccentricity with the sun at one of the foci, completing one revolution in one year. The axis of rotation of the earth is inclined at about 23½ degrees with respect to the plane of orbital revolution and is directed always to a fixed point in space. As a consequence of this geometry of the sun and the earth, large seasonal variations occur in the amount of solar radiation received at different latitudes of the earth. The largest annual variations occur near the two poles and the smallest near the equator. During the course of its annual motion around the sun in an elliptical orbit, the earth comes nearest to the sun each year around January 5 (perihelion) and farthest around July 5 (aphelion). The sun-earth distance at perihelion is

$1.471 \times 10^8$ km and at aphelion $1.521 \times 10^8$ km. The mean distance is $1.496 \times 10^8$ km, which is known as 1 Astronomical Unit. Due to the variations in the sun-earth distance, the solar radiation intercepted by the earth varies by ±3.3 per cent around the mean value, being maximum at the beginning of January and minimum at the beginning of July.

Of the entire quantity of radiant energy emitted by the sun's spherical surface, only a small fraction ($4.5 \times 10^{-10}$) is actually intercepted by the planet earth. The amount of solar energy falling in unit time on unit area, held normal to the sun's rays outside the earth's atmosphere when the earth is at the mean distance from the sun, is called the solar constant. According to the latest measurements, the solar constant has a value of 136 mW/cm$^2$ or 1.36 kW/m$^2$ or 1.95 calories/cm$^2$ per minute.

## 2.2 Interaction of the sun's radiation with the earth's atmosphere

Since the earth is surrounded by an atmosphere which contains various gaseous constituents, suspended dust and other minute solid and liquid particulate matter and clouds of various types, marked depletion of solar energy takes place during its passage through the atmosphere to the surface of the earth. In a cloud-free atmosphere, the depletion occurs by three distinct physical processes operating simultaneously: (i) selective absorption by molecular oxygen, ozone, carbon dioxide, and water vapour in certain specific wavelengths, (ii) Rayleigh scattering by molecules of the different gases that constitute the atmosphere, and (iii) Mie scattering. In Rayleigh scattering, where the size of the scattering particles is small compared with the wavelength of light, the intensity of scattering follows the well-known λ–4 law, as a consequence of which a spatial redistribution of the energy of the incoming radiation takes place in the scattered light, the shorter wavelengths predominating and giving rise to the blue of the sky.

Roughly one half of the scattered radiation is lost to space and the remaining half is directed downwards to the earth's surface from different directions as diffuse radiation. In Mie scattering where the sizes of the scattering particles, mostly dust, are comparable with the wavelength of visible and infrared radiation, a depletion in the solar radiation occurs both by true scattering (involving a redistribution of incident energy) as well as by absorption by the particles, wherein a part of the radiant energy is transformed into heat. This type of scattering also leads to a fraction of the solar radiation being lost to space and another fraction being directed downwards as diffuse radiation. Unlike Rayleigh scattering, however, the dust-scattering process is more complicated and the redistribution of energy is much more asymmetrical with respect to the different directions when compared to Rayleigh scattering. Because of absorption by oxygen and ozone at high levels of the atmosphere, the short-wavelength limit of solar radiation received at the earth's surface is approximately 0.29 μ.

In a cloudy atmosphere, considerable depletion of the direct solar radiation takes place. A large fraction is reflected back to space from the tops of clouds, another part transmitted downwards to the earth as diffuse radiation and a small fraction absorbed by the clouds. Dense dark clouds of appreciable vertical depth can cut off as much as 80 per cent of the incident energy, but thinner clouds deplete only 20–50 per cent of the radiant energy, depending on their depth and liquid water content. The effect of an increase in dust in the atmosphere is to decrease the direct solar radiation and increase the diffuse radiation. When the cloud amount increases from 0 to about 4 or 5 octas of the sky, there is a corresponding increase in diffuse radiation. However, when the cloud amount increases still further to overcast conditions, a decrease in diffuse radiation takes place, largely because of increased absorption and reflection from cloud tops. The fraction of the total solar radiant energy reflected back to space through reflection from the tops of clouds, scattering by atmospheric gases and dust particles and by reflection at the earth's surface is called the albedo of the earth-atmosphere system and has a value of about 0.30 for the earth as a whole. The mean monthly value of the intensity of direct solar radiation normal to the solar beam actually received at the earth's surface at noon time in India varies from 0.51 to 1.05 $kW/m^2$, depending on latitude, altitude of the station, and season.

The solar radiant energy in the shortwave spectrum falling on the earth's surface as well as that absorbed by the atmosphere is re-emitted back into space as longwave radiation.

This longwave radiation has the characteristics of blackbody radiation in the temperature range of about –60° to +30°C. Since, in the long run, the earth's mean surface temperature as well as the mean temperature of the atmosphere remains unchanged, it follows that the net heat absorbed by the earth–atmosphere system from the shortwave solar radiation is equal to the net heat emitted as longwave radiation by the planet earth and its atmosphere.

## 2.3 Terminology of radiation parameters

For practical purposes it is convenient to divide the entire radiation regime within the earth's atmosphere into two parts, the solar or shortwave radiation and the terrestrial or longwave radiation. This is possible because solar radiation corresponds approximately to blackbody radiation at about 6000°K, the energy of which is almost entirely (99 per cent) confined to wavelengths less than 4 μ, while the radiation emitted by the earth and its atmosphere, which corresponds approximately to blackbody radiation at temperatures less than 300°K, has, for all practical purposes, its energy between the wavelength limits 4–100 μm. Thus, a division of the spectrum at about 4 μm effectively separates the solar and terrestrial radiation as shortwave and longwave radiation. The different radiation parameters are defined below:

1. Direct solar radiation at normal incidence, IN, is the quantity of shortwave solar radiant energy emitted by the solid angle subtended by the visible disc of the sun and passing through a unit area held normal to the solar beam at the earth's surface in unit time.
2. Global solar radiation, G, is the total quantity of shortwave radiant energy emitted by the sun's disc as well as that scattered diffusively by the atmosphere and clouds passing through a unit area in the horizontal in unit time. The global solar radiation is also referred to as incoming total shortwave radiation, K↓.
3. Direct solar radiation on a horizontal surface, IH, is the quantity of solar radiant energy emitted from the solid angle subtended by the visible disc of the sun and passing through a unit area in the horizontal in unit time. This is also called the vertical component of the direct solar radiation.
4. Diffuse solar radiation, D, is that part of shortwave radiation scattered by the atmosphere reflected diffusely and transmitted by clouds and passing through unit horizontal area in unit time. This radiation comes from a solid angle of 2π with the exception of the solid angle subtended by the sun's disc. There is a simple relation between G, D and IH and IN, given by:

$$I_H = (G - D) \text{ and } I_N = \frac{(G - D)}{\sin h}$$

   where, h is the angle of elevation of the sun.
5. Reflected solar radiation, K↑, is that part of the incoming shortwave radiation which is reflected by the earth's surface and diffused by the atmospheric layer between the ground and the point of observation. The albedo of the earth's surface, A, is expressed as the ratio of the reflected solar radiation to the global solar radiation,

$$A = \frac{K\uparrow}{G}.$$

6. Upward longwave radiation, L↑, is the quantity of longwave radiation emitted upwards by the earth's surface and the shallow layer of atmosphere below the level of the measuring instrument, and passing through unit area in the horizontal in unit time.

7. Downward longwave radiation, L↓, is the longwave radiation emitted downwards by the earth's atmosphere and passing through a unit horizontal area at the level of the instrument in unit time.
8. Net longwave radiation, L*, is the difference between the outgoing and incoming longwave radiation and is given by L* = L↑ – L↓.
9. Net radiation, Q*, is the difference between the total incoming short and longwave radiation and the outgoing short and longwave radiation and is given by Q* = K↓ – K↑ + L↓ – L↑.

Other radiation parameters of interest are direct, global or diffuse solar radiation in restricted portions of the solar spectrum and various atmospheric turbidity factors.

### 2.3.1 Latitude

The latitude of a location on the earth is the angular distance of that location south or north of the equator. The latitude is an angle, and is usually measured in degrees (marked with °). The equator has a latitude of 0°, the North pole has a latitude of 90° north (written 90°N or +90°), and the South pole has a latitude of 90° south (written 90°S or –90°). Together, latitude and longitude can be used as a geographic coordinate system to specify any location on the globe. Curves of constant latitude on the earth (running east-west) are referred to as lines of latitude or parallels. Each line of latitude is actually a circle on the earth parallel to the equator, and for this reason lines of latitude are also known as circles of latitude. In spherical geometry, lines of latitude are examples of circles of a sphere, with the equator being a great circle.

Latitude [usually denoted by the Greek letter phi (φ)] is often measured in degrees, with minutes and seconds for finer measurements. For example, the Eiffel Tower has a latitude of 48° 51′ 29″ N—that is, 48 degrees plus 51 minutes plus 29 seconds. Alternatively, latitude may be measured entirely in degrees, e.g. 48.85806° N. Besides the equator, four other lines of latitude are commonly used to mark maps of the earth. Each of these lines plays an important role in the geometrical relationship between the earth and the sun:

1. Arctic circle: 66° 33′ 39″ N.
2. Tropic of Cancer: 23° 26′ 21″ N.
3. Equator: 0° Latitude.
4. Tropic of Capricorn: 23° 26′ 21″ S.
5. Antarctic Circle: 66° 33′ 39″ S.

*Effect of latitude:* A region's latitude has a great effect on its climate and weather. Latitude more loosely determines prevailing winds, and other physical characteristics of geographic locations. Auroral activity is common at high geomagnetic latitudes. Some observers have noted a correlation between the latitude of a country and its economic activity.

### 2.3.2 Declination

Declination is one of the two coordinates of the equatorial coordinate system, the other being either right ascension or hour angle. Declination in astronomy is comparable to geographic latitude, but projected onto the celestial sphere. Declination is measured in degrees north and south of the celestial equator. Points north of the celestial equator have positive declinations, while those to the south have negative declinations (Fig. 2.1).

1. An object on the celestial equator has a declination of 0°.
2. An object at the celestial north pole has a declination of +90°.
3. An object at the celestial south pole has a declination of –90°.

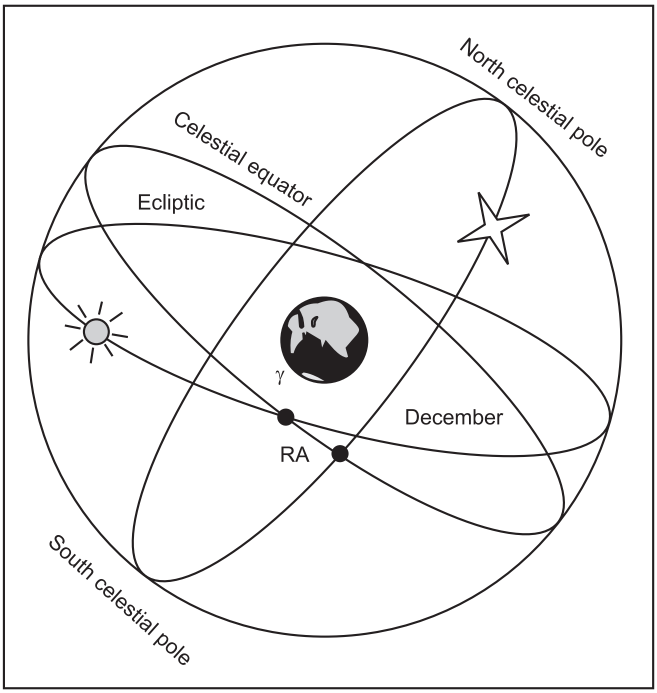



**Figure 2.1** Declination

The sign is customarily included even if it is positive. Any unit of angle can be used for declination, but it is often expressed in degrees, minutes, and seconds of arc.

A celestial object directly overhead (at the zenith) has a declination very nearly equal to the observer's latitude. A pole star therefore has the declination near to +90° or –90°. At northern latitudes φ (φ = observer's latitude) >0, celestial objects with a declination greater than 90° – φ are always visible. Such stars are called circumpolar stars, while the phenomenon of the sun not setting is called midnight sun.

When an object is directly overhead its declination is almost always within 0.01 degree of the observer's latitude; it would be exactly equal except for two complications. The first complication applies to all celestial objects: the object's declination equals the observer's astronomic latitude, but the term 'latitude' ordinarily means geodetic latitude, which is the latitude on maps and GPS devices. The difference usually doesn't exceed a few thousandths of a degree, but in a few places (such as the big island of Hawaii) it can exceed 0.01 degree.

For practical purposes the second complication only applies to solar system objects: 'declination' is ordinarily measured at the center of the earth, which is not quite spherical, so a line from the center of the earth to the object is not quite perpendicular to the earth's surface.

It turns out that when the moon is directly overhead its geocentric declination can differ from the observer's astronomic latitude by up to 0.005 degree. The importance of this complication is inversely proportional to the object's distance from the earth, so for most practical purposes it is only a concern with the moon.

The declination of the sun, dO·, is the angle between the rays of the sun and the plane of the earth's equator. The earth's axial tilt (called the obliquity of the ecliptic by astronomers) is the angle between the earth's axis and a line perpendicular to the earth's orbit. The earth's axial tilt changes gradually over thousands of years, but its current value is about ε = 23°26′. Because this axial tilt is nearly constant, solar declination (dO·) varies with the seasons and its period is one year.

### 2.3.3 Azimuth

An azimuth is an angular measurement in a spherical coordinate system. The vector from an observer (origin) to a point of interest is projected perpendicularly onto a reference plane; the angle between the projected vector and a reference vector on the reference plane is called the azimuth (Fig. 2.2).

An example of an azimuth is the measurement of the position of a star in the sky. The star is the point of interest, the reference plane is the horizon or the surface of the sea, and the reference vector points to the north. The azimuth is the angle between the north point and the perpendicular projection of the star down onto the horizon. Azimuth is usually measured in degrees (°). The concept is used in many practical applications including navigation, astronomy, engineering, mapping, mining and artillery.

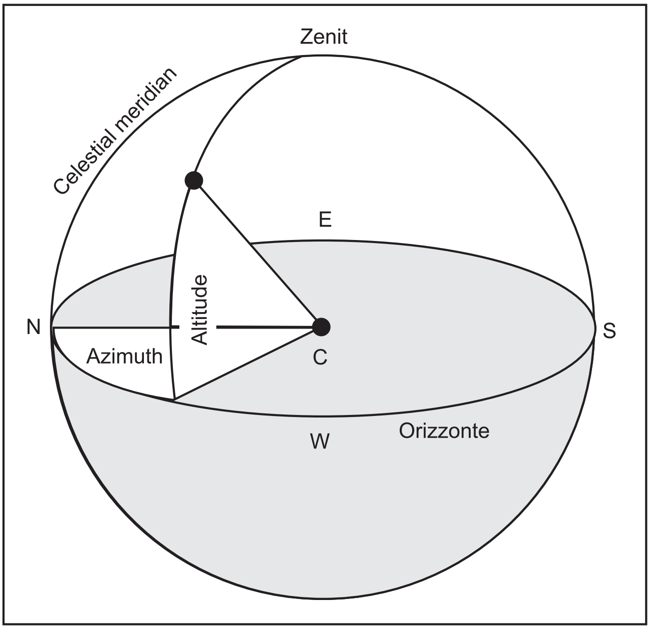



**Figure 2.2** The azimuth is the angle that start from North direction, indicated here as 45 degrees

In land navigation, azimuth is usually denoted as alpha (α), and defined as a horizontal angle measured clockwise from a north base line or meridian. Azimuth has also been more generally defined as a horizontal angle measured clockwise from any fixed reference plane or easily established base direction line. Today, the reference plane for an azimuth in a general navigational context is typically true north, measured as a 0° azimuth, though other angular units (grad, mil) can also be employed. In any event, the azimuth cannot exceed the highest number of units in a circle—for a 360° circle, this is 359 degrees, 59 arcminutes, 59 arcseconds (359° 59′ 59″).

For example, moving clockwise on a 360° degree circle, a point due east would have an azimuth of 90°, south 180°, and west 270°. However, there are exceptions: some navigation systems use geographic south as the reference plane. Any direction can potentially serve as the plane of reference, as long as it is clearly defined for everyone using that system.

### 2.3.4 Solar azimuth angle

The solar azimuth angle is the azimuth angle of the sun. It is most often defined as the angle from due north in a clockwise direction. It can be calculated, to a good approximation, using the following formula, however angles should be interpreted with care due to the inverse sine, i.e. $x = \sin^{-1}(y)$ has more than one solution, only one of which will be correct.

$$\sin \phi_s = \frac{-\sin h \cos \delta}{\cos \theta_s}$$

The following two formulas can also be used to approximate the solar azimuth angle, however because these formulas utilize cosine, the azimuth angle will always be positive, and therefore, should be interpreted as the angle less than 180 degrees when the hour angle, h, is negative (morning) and the angle greater than 180 degrees when the hour angle, h, is positive (afternoon).

$$\cos \phi_s = \frac{\sin \delta \cos \Phi - \cos h \cos \delta \sin \Phi}{\cos \theta_s}$$

$$\cos \phi_s = \frac{\sin \delta - \sin \theta_s \sin \Phi}{\cos \theta_s \cos \Phi}$$

The previous formulas use the following terminology:

$\phi_s$ is the solar azimuth angle.
$\theta_s$ is the solar elevation angle.
h is the hour angle of the present time.
$\delta$ is the current sun declination.
$\Phi$ is the local latitude.

### 2.3.5 Hour angle

The hour angle is one of the coordinates used in the equatorial coordinate system to give the position of a point on the celestial sphere. The hour angle of a point is the angle between two planes: one containing the earth's axis and the zenith (the meridian plane), and the other containing the earth's axis and the given point. The angle is negative east of the meridian plane and positive west of the meridian plane or it can be positive westward zero to 360 degrees. The angle may be measured in degrees or in time, with 24 hours equalling 360 degrees exactly. The hour angle is paired with the declination to fully specify the position of a point on the celestial sphere. The hour angle (HA) of an object is equal to the difference between the current local sidereal time (LST) and the right ascension ($\alpha$) of that object:

$$HA_{object} = LST - \alpha_{object}$$

Thus, the object's hour angle indicates how much sidereal time has passed since the object was on the local meridian. It is also the angular distance between the object and the meridian, measured in sidereal hours (1 hour = 15 degrees). For example, if an object has an hour angle of 2.5 hours, it crossed the local meridian 2.5 sidereal hours ago (i.e. hours measured using sidereal time), and is currently 37.5 degrees west of the meridian. Negative hour angles indicate the time until the next transit across the local meridian. Of course, an hour angle of zero means the object is currently on the local meridian.

### 2.3.6 Solar hour angle

The hour angle (h or ha) of a point on the earth's surface is the angle through which the earth would turn to bring the meridian of the point directly under the sun. The earth is rotating, so this angular displacement represents time. So in observing the sun from earth, the solar hour angle is an expression of time, expressed in angular measurement, usually degrees, from the solar noon.

At solar noon, at the observer's longitude on earth, the hour angle is 0.000 degrees with the time before solar noon expressed as negative degrees, and the local time after solar noon expressed as positive degrees. The hour angle is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour with morning being negative and afternoon being positive. For example, at 10:30 a.m. local apparent time the hour angle is –22.5° (15° per hour times 1.5 hours before noon).

The cosine of the hour angle [cos(h)] becomes an easy computation tool in determining the cosine term for the computation of the angle of the sun's altitude (or the complementary zenith angle) at any time during the day. At solar noon, h = 0.000 so of course, cos(h) = 1, and before and after solar noon the cos(± h) term = the same value for morning (negative hour angle) or afternoon (positive hour angle), i.e. the sun is at the same altitude in the sky at both 11:00 am and 1:00 pm solar time, etc.

### 2.3.7 Local mean time

Local mean time is a form of solar time that corrects the variations of local apparent time, forming a uniform time scale at a specific longitude. Its uniformity depends only on the accuracy of the clocks used to measure it. Local mean time was used from the early 19th century, when local solar time or sundial time was last used, until standard time was adopted on various dates in the several countries. Standard time means that the same time is used throughout some region—usually, it was either offset from Greenwich Mean

Time or was the local mean time of the capital of the region. The difference between local mean time and local apparent time is the equation of time.

### 2.3.8 Solar time

Time of day as determined by the position of the sun in the sky. Apparent solar time, the time given by a sundial, is not uniform because of the varying speed of the earth in its elliptical orbit. Mean solar time is a uniform time that coincides with apparent solar time at four instants through the year. The difference between them is known as the equation of time, and is greatest in early November when the sun is more than 16 minutes fast on mean solar time. Mean solar time on the Greenwich meridian is known as Greenwich Mean Time and is the basis of civil timekeeping.

## 2.4 Apparent motions of the sun

During the year the earth moves around the sun. As a result, the sun appears to move around the sky once with respect to the stars as seen from earth. Earth takes about 365 and a quarter days to travel once around the sun. Since the earth moves around the sun and we are resident on the earth, it means that the sun appears to shift in the sky about 1 degree per day. This number is calculated by taking the total degrees in a circle (360 degrees, since the earth moves 360 degrees around the sun) and dividing that amount by the total number of days in a year (365.2422). The result is 360 degree/365.2422 days to equal about 1 degree per day.

The plane of the earth's orbit is called the ecliptic. Since the earth orbits the sun, the sun is also on the ecliptic. As a result, the sun appears to us to move around the sky on the ecliptic.

Please note that the ecliptic is not the same thing as the earth's extended equator, the celestial equator. The earth's axis (and hence also the celestial equator) is actually tilted by 23.5 degrees with respect to the plane of the earth's orbit or the ecliptic. If we consider the celestial equator as the reference circle, the ecliptic appears to be inclined or tilted, 23.5 degrees from the plane of the earth's equator, as demonstrated above. This orientation means that the sun appears to transit the sky north of the celestial equator during part of the year and south of the celestial equator the other part of the year.

## 2.5 Day length

Day length or length of day or length of daytime, refers to the time each day from the moment the upper limb of the sun's disk appears above the horizon during sunrise to the moment when the upper limb disappears below the horizon during sunset. Due to the diffusion and refraction of sunlight by the atmosphere, there is actually daylight even when the sun is slightly below the horizon. The period when it is still somewhat light even though the sun is below the horizon is called twilight. In general, the length of a day varies throughout the year, and depends upon latitude. This variation is caused by the tilt of the earth's axis of rotation with respect to the ecliptic plane of the earth around the sun. At the solstice occurring about June 20–22, the north pole is tilted toward the sun, and therefore the northern hemisphere has days ranging in duration from just over 12 hours in the southern portion of the Tropic of Cancer to 24 hours in the Arctic Circle, while the southern hemisphere has days ranging in duration from just under 12 hours in the northern portion of the Tropic of Capricorn to zero in the Antarctic Circle.

At the equinox occurring about September 22–23, the poles are neither tilted toward nor away from the sun, and the duration of a day is generally about 12 hours all over the earth. At the solstice occurring about December 20–22, the south pole is tilted toward the sun, and therefore the southern hemisphere has days ranging in duration from just over 12 hours in the northern portion of the Tropic of Capricorn to 24 hours in the Antarctic Circle, whereas the northern hemisphere has days ranging in duration from just under 12 hours in the southern portion of the Tropic of Cancer to zero in the Arctic Circle. At the equinox occurring about March 19–21, the poles are again aligned so that the duration of a day is generally about 12 hours all over the earth.

In each hemisphere, the higher the latitude, the shorter the day during winter. Between winter and summer solstice, the day's duration increases, and the rate of increase is larger the higher the latitude. A fast increase of day length is what allows a very short day on winter solstice at 60 degrees latitude (either north or south) to reach about 12 hours by the spring equinox, while a slower increase is required for a much longer day on winter solstice at 20 degrees latitude (again, either north or south) to reach 12 hours by the spring equinox. The rate of change of day duration is generally fastest at the equinoxes, although at high latitudes the change is similar for several weeks before and after the equinoxes. The rate of change of day duration at each solstice is zero as the change goes from positive to negative or vice versa. Some interesting facts are as follows:

1. On the equator, the duration of daylight is not exactly 12 hours all the year round, but rather—due to atmospheric refraction and the size of the Sun—exceeds 12 hours by about 7 minutes each day.
2. Because the sun is north of the equator for almost 4 days more than half the year, the duration of the average day at a given latitude in the northern hemisphere exceeds the duration of the average day at the same latitude in the southern hemisphere by a few minutes.

3. During a few days around the equinoxes—about March 19–22 and September 21–24—both poles experience simultaneously 24 hours of daytime, due mainly to atmospheric refraction.
4. Each pole has only one sunrise and one sunset per year, around the time of the equinoxes. Each pole's sunrise is nearly coincident with the other's sunset, with minor differences due mainly to atmospheric refraction.

## 2.6 Solar energy reaching the earth's surface

### 2.6.1 Solar Constant

The sun is considered to produce a constant amount of energy. At the surface of the Sun the intensity of the solar radiation is about $6.33 \times 10^7$ W/m$^2$ (note that this is a power, in watts, per unit area in metres).

As the sun's rays spread out into space the radiation becomes less intense and by the time the rays reach the edge of the earth's atmosphere they are considered to be parallel.

The solar constant ($I_{SC}$) is the average radiation intensity falling on an imaginary surface, perpendicular to the sun's rays and at the edge of the earth's atmosphere (Fig. 2.3). The word 'constant' is a little misleading since, because of the earth's elliptical orbit the intensity of the solar radiation falling on the earth changes by about 7 per cent between January 1st, when the earth is nearest the sun, and July 3rd, when the earth is furthest from the sun. A yearly average value is thus taken and the solar constant equals 1367 W/m$^2$. Even this value is inaccurate since the output of the sun changes by about ±0.25 per cent due to sun spot cycles.

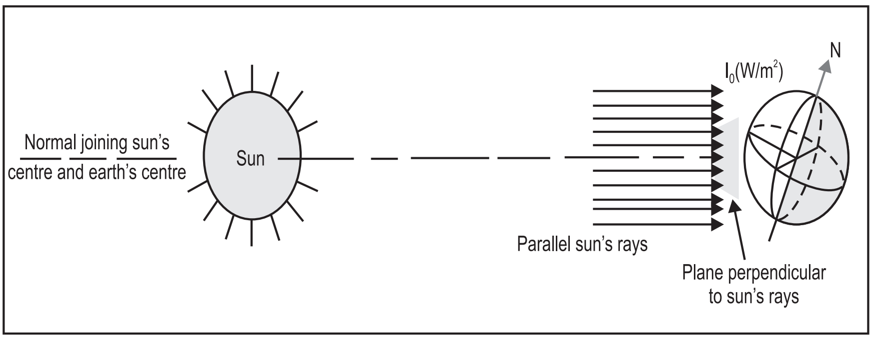



**Figure 2.3** The sun's rays incident on the earth. I0 = irradiance on a plane perpendicular to the sun's rays

The solar radiation intensity falling on a surface is called irradiance or insolation and is measured in $W/m^2$ or $kW/m^2$.

The solar constant can be used to calculate the irradiance incident on a surface perpendicular to the sun's rays outside and the earth's atmosphere (Fig. 2.3) on any day of the year (i.e. as the distance between the sun and earth changes throughout the year):

$$I_0 = I_{SC}\left[1 + 0.034\cos\left(2\pi\frac{n}{365.25}\right)\right] \quad \text{... (2.1)}$$

where,

$I_0$ = extraterrestrial (outside the atmosphere) irradiance on a plane perpendicular to the sun's rays ($W/m^2$).

$I_{SC}$ = the solar constant (1367 $W/m^2$).

n = the day of the year such that for January the 1st n = 1.

Figure 2.4 shows the variation in $I_0$ over the course of a year. Most solar power calculations use $I_0$ as a starting point because, for any given day of the year it is the maximum possible energy obtainable from the sun at the edge of the earth's atmosphere.

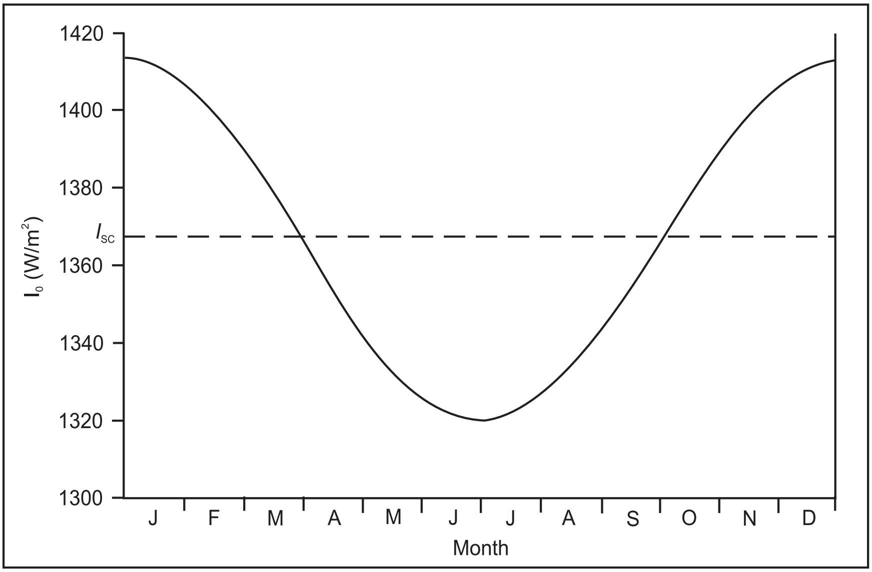



**Figure 2.4** The variation in $I_0$ over the course of a year. The dashed line shows the value of the solar constant (ISC)

### 2.6.2 Cosine Effect

The value of I0 is the same no matter where you are on the earth's surface, however not all points on the earth's surface are perpendicular to the sun's rays. A useful quantity to calculate is the solar irradiance incident on an imaginary surface that is parallel to a horizontal plane on the earth's surface (Fig. 2.5). The irradiance on such a surface is smaller than $I_0$ because of the cosine effect and is the maximum amount of solar energy that could be collected on a horizontal plane at the earth's surface if the atmosphere did not scatter and absorb any radiation.

Figure 2.5 shows three plane surfaces:

1. Plane A, a horizontal plane at the point P on the earth's surface.
2. Plane B, a surface parallel to plane A but on the edge of the earth's atmosphere, often referred to as the horizontal plane.
3. Plane C, a surface perpendicular to the sun's rays, often referred to as the normal plane.

$I_0$ is the irradiance intensity on the normal plane and the irradiance intensity on the horizontal plane can be calculated from:

$$I_{0h} = \cos \theta_z \qquad \text{... (2.2)}$$

where $\theta_z$ is the solar zenith angle described already and $I_{0h}$ is the extraterrestrial irradiance intensity on the horizontal plane. It can be seen in Fig. 2.2, the qz is also the angle of incidence of the sun's rays on a horizontal plane. Note that since cosine values fall between 1 and –1, $I_{0h}$ will never be greater than $I_0$, and $I_{0h}$ = I0 at point P′ where $\cos \theta_z = 1$ ($\theta_z = 0°$).

### 2.6.3 Irradiation

Just to be confusing the intensity of solar radiation is called irradiance and is measures in the units of power per unit area ($W/m^2$ or $kW/m^2$) however, the total amount of solar radiation energy is called irradiation and is measures in the units of energy per unit area ($J/m^2$). Irradiation is given the symbol H, so that:

1. $H_0$ is the total daily amount of extraterrestrial radiation on a plane perpendicular to the sun's rays.
2. $H_{0h}$ is the total daily amount of extraterrestrial radiation on a plane horizontal to the earth's surface.

Note that these planes are considered to rotate with the earth so that $H_0$ and $H_{0h}$ are daily values, and the planes are shaded at night. Figures 2.6 and 2.7 show how the values of $H_0$ and $H_{0h}$ vary throughout the year in the northern hemisphere. Note that for any given day the value of $H_0$ changes from latitude to latitude despite the value of $I_0$ being constant for all latitudes. This occurs because the length of the days changes and the effects is most obvious inside the Arctic circle where much of the year is either 24 hours of darkness or 24 hours of daylight.

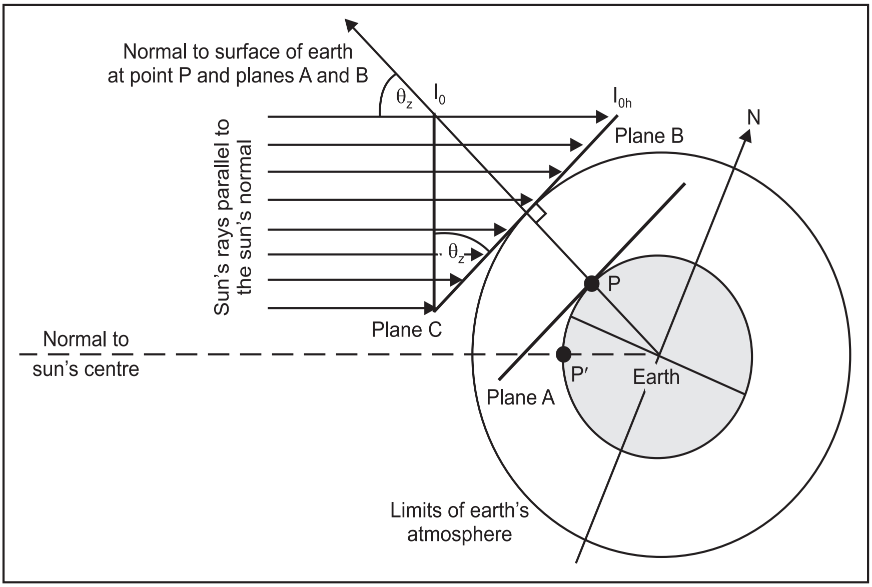



**Figure 2.5** The cosine effect

## 2.6.4 Solar spectrum

The sun's radiation is a good approximation of black body radiation (a continuous distribution of wavelengths with no wavelengths missing) with wavelengths in the range of about 0.2 μm to 2.6 μm (Fig. 2.8). The solar spectrum consists of ultraviolate rays in the range of 200–400 nm, visible light in the range 390 nm (violet) to 740 nm (red) and the infra red in the range 700 nm to 1 mm. Table 2.1 shows the subdivisions of the ultraviolate range and Table 2.2 shows the distribution of extraterrestrial solar radiation.

**Table 2.1** Subdivision of ultraviolate radiation.

| | | |
|---|---|---|
| UV-A | 320–400 nm | Not harmful in normal doses, vitamin D production |
| UV-B | 290–320 nm | Tanning, can burn |
| UV-C | 230–290 nm | Causes skin cancer |

**Table 2.2** Distribution of extraterrestrial solar radiation.

| | | |
|---|---|---|
| Ultraviolet | 200–400 nm | 8.7% |
| Visible | 400–700 nm | 38.3% |
| Near infrared | 700–3500 nm | 51.7% |

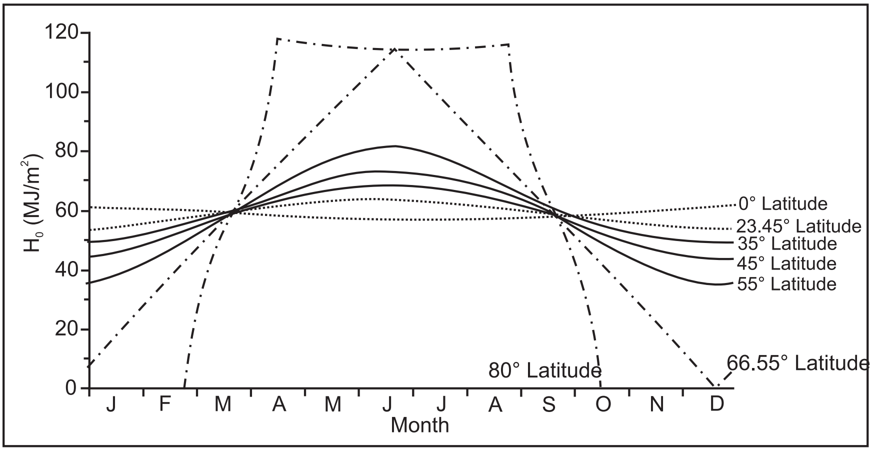



**Figure 2.6** The total daily amount of extraterrestrial irradiation on a plane perpendicular to the sun's rays ($H_0$) for different latitudes

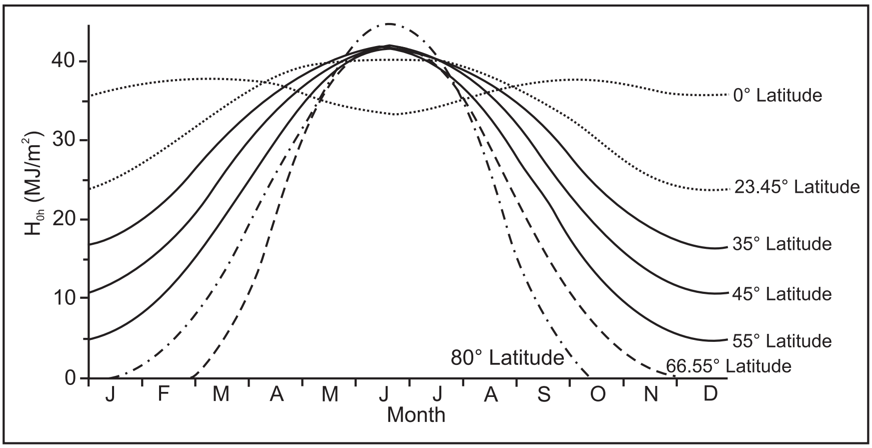



**Figure 2.7** The total daily amount of extraterrestrial irradiation on a plane horizontal to the earth's surface ($H_{0h}$) for different latitudes

As the sun's rays pass through the atmosphere certain wavelengths are absorbed and a proportion of the total energy is scattered. Thus the solar spectrum at the earth's surface has some wavelengths missing (shown as dark portion in Fig. 2.8) and the overall intensity is reduced.

## 2.6.5 Atmosphere and air mass

The atmosphere scatters and absorbs some of the sun's energy that is incident on the earth's surface. Scattering of radiation by gaseous molecules (e.g. $O_2$, $O_3$, $H_2O$ and $CO_2$), that are a lot smaller than the wavelengths of the radiation, is called Rayleigh scattering. Roughly half of the radiation that is scattered is lost to outer space, the remaining half is directed towards the earth's surface from all directions as diffuse radiation. Because of absorption by oxygen and ozone molecules the shortest wavelength that reaches the earth's surface is approximately 0.29 μm. Other gas molecules absorbed difference wavelengths as indicated in Fig. 2.8.

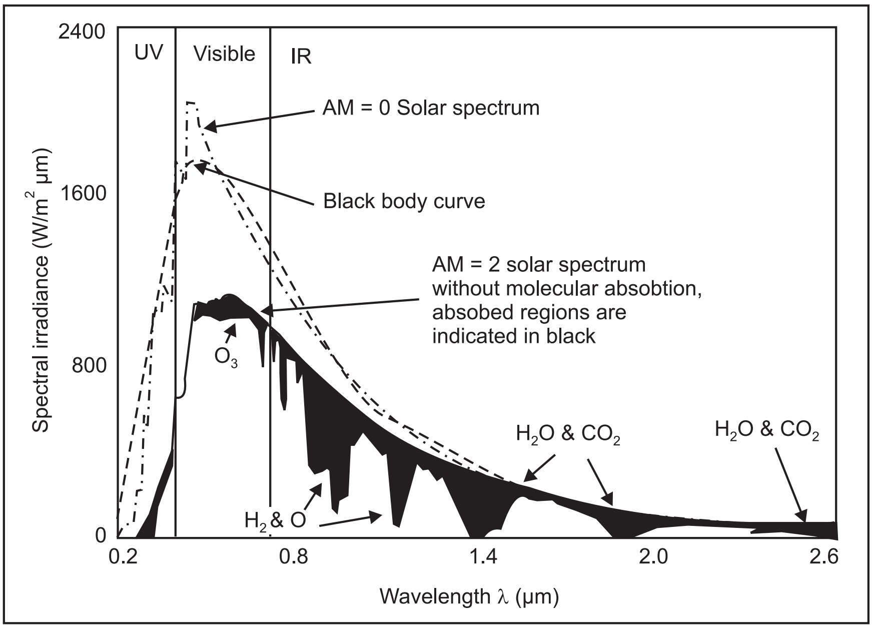



**Figure 2.8** The extraterrestrial solar spectrum (AM = 0), the theoretical black body curve and the solar spectrum at the earth's surface for AM = 2 and the absorbed regions shown in black

Scattering by dust particles larger than wavelengths of light is called Mie scattering. This process includes both true scattering (where the radiation bounces of the particle) and absorption followed by emission, which heats the particles. The amount of radiation scattered by this process will vary a lot depending on location and the weather blowing particles about. A form of Mie scattering called the Tyndall effect, which preferentially scatters shorter wavelengths, is responsible for the sky being blue.

Clouds reflect a lot of radiation and also absorbed a little, the rest is transmitted through. Globally, clouds reflect a lot of radiation and help regulate the surface temperature.

The fraction of the total solar radiant energy reflected back to space from clouds, scattering and reflection from the earth's surface is called the albedo of the earth-atmosphere system and is roughly 0.3 for the earth as a whole. Figure 2.9 shows that a plane on the earth's surface receives

1. Beam (or direct) radiation—coming straight through the atmosphere to hit the plane (very directional).
2. Diffused radiation—scattered in all direction in the atmosphere and then some arrives at the plane on the earth's surface (not directional).
3. Reflected radiation—beam and diffused radiation that hits the earth's surface and is reflected onto the plane.

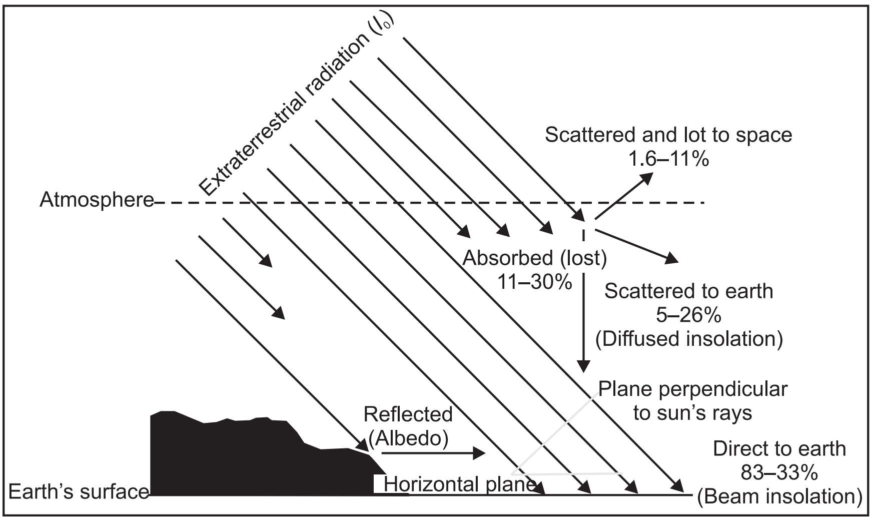



**Figure 2.9** The effect of the atmosphere on the solar radiation reaching the earth's surface

The amount of energy reflected, scattered and absorbed depends on the amount of atmosphere that the incident radiation travels through as well as the levels of dust particles and water vapour present in the atmosphere. The latter is difficult to judge but the distance travelled through the atmosphere by incident radiation depends on the angle of the sun (Fig. 2.10).

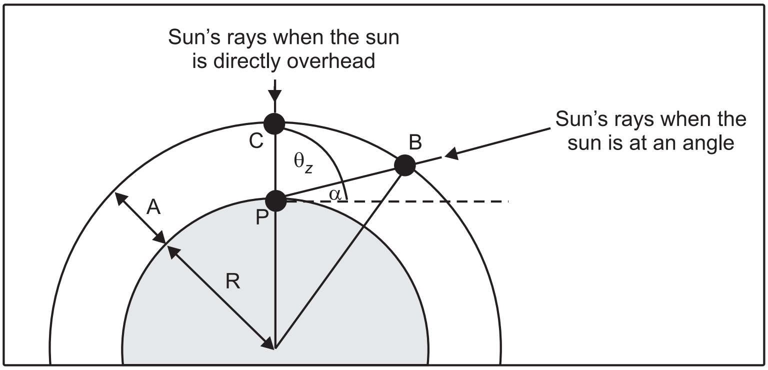



**Figure 2.10** The distance travelled through the atmosphere by the sun's rays

The distance travelled through the atmosphere by the sun's rays incident on the earth is accounted for by a quantity called air mass (AM).

$$\text{Air mass} = \frac{\text{Path length travelled}}{\text{Verticle depth of the atmosphere}}$$

$$AM = \frac{BP}{CP} = \left[\left(\frac{R}{H}\cos\theta_z\right)^2 + 2\frac{R}{H} + 1\right]^{1/2} - \left(\frac{R}{H}\right)\cos\theta_z \qquad \text{... (2.3)}$$

where,

R = the radius of the earth, taken to be 6370 km.

H = thickness of atmosphere, taken to be 7991 km (although it is considerably thicker at the equator than the poles).

For angles of $\theta_z < 70°$.

$$AM \approx \frac{1}{\cos\theta_z} = \sec\theta_z \qquad \text{... (2.4)}$$

Therefore, outside the earth's atmosphere AM = 0, when the sun is directly overhead $\theta_z = 0$, AM = 1 and when the $\theta_z = 60°$ AM = 2. AM is normally taken to be an average of 1.5 for a clear sunny day and this value is used for the calibration of solar cells.

## 2.6 Rough estimates of the solar energy available at the earth's surface

The solar constant is the average extraterrestrial insolation at the edge of the atmosphere:

$$I_{SC} = 1367 \text{ W/m}^2$$

The earth presents a disc of area $\pi R_2$ to the sun, therefore the total amount of extraterrestrial insolation incident on the earth is $I_{SC} \times \pi R^2$. This value is then divided by half the surface areas of the earth, $4\pi R^2/2$, which gives 684 W/m$^2$, the average insolation incident on unit area of the earth facing the sun (Fig. 2.11). Note that solar panels are calibrated assuming that there is 1000 W/m$^2$ available.

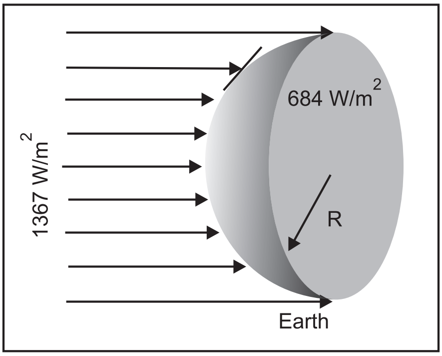



**Figure 2.11** The average insolation incident on unit area of the earth facing the sun

A rough estimate of the irradiation incident per unit area (H) of the earth's surface can be made if we assume that 30 per cent of the sun's energy is lost in the atmosphere and that a day is an average of 12 hours long at any location.

$$H = 0.7 \times 684 \times 12 = 5.75 \text{ kWh/day}$$

Or if we assume that the sun is only at an appreciable strength for an average 6 hours in the day (as is likely in more northerly latitudes):

$$H = 0.7 \times 684 \times 6 = 2.88 \text{ kWh/day}$$

Figure 2.12 shows the yearly profile of mean solar radiation for different locations around the world. The solid grey line show the value of 5.75 kWh/day and the dashed grey line shows 2.88 kWh/day.

## 2.7 Earth–Sun geometry

We need to assess the flux density of solar radiation on flat and inclined surfaces for a variety of biometeorological problems. This information is used to compute the energy balance, evaporation and photosynthesis rates and stomatal conductance of inclined leaves, and plants. In this section we will cover issues relating to cosine laws between the incident and received rays and learn to compute angles between the sun and the normal to points on earth.

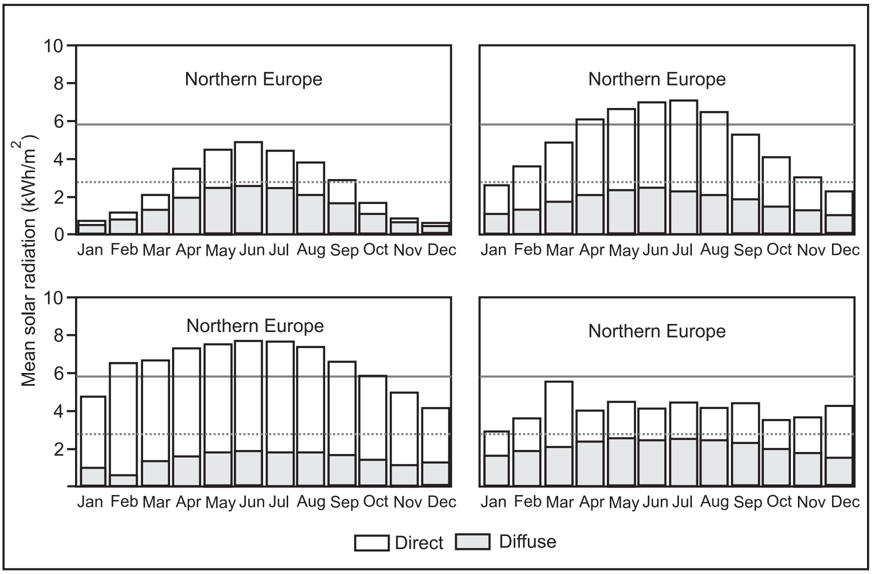



**Figure 2.12** The yearly profile of mean solar radiation for different locations around the world

## 2.7.1 Lambert's Cosine Law

The flux density radiation on the horizontal is a function of the angle between the surface normal and the direction of the ray is defined by Lambert's Cosine Law:

$$R(i) = R_{\perp} \cos(\gamma) = R_{\perp} \sin(\beta)$$

Definition of zenith and elevation angles and the projection of area normal to incident rays on a flat surface are shown in Fig. 2.13.

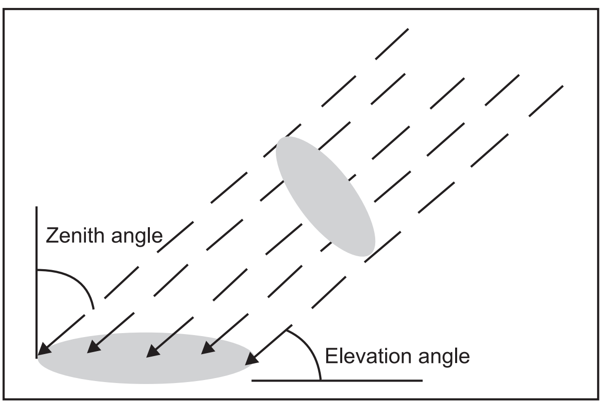
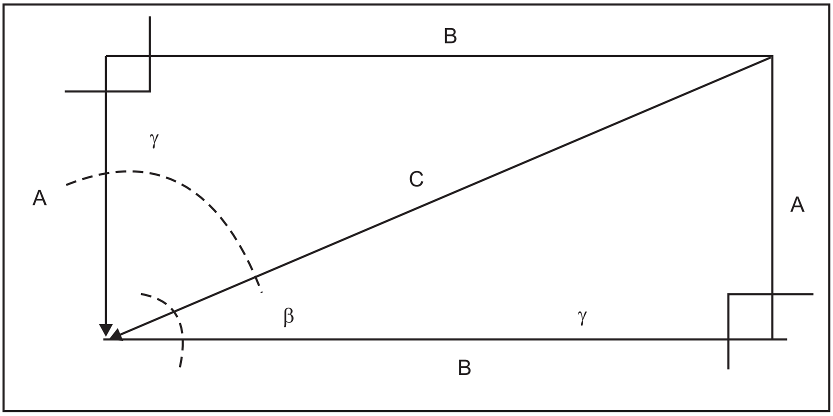



**Figure 2.13** Definition of zenith and elevation angles and the projection of area normal to incident rays on a flat surface

The ratio between the flux density of radiation on the horizontal surface to the flux density normal to the incoming radiation is related to the ratios of the areas of the beam cross section and the projected horizontal area.

$$R(i) = R_{\perp} \frac{A_{beam}}{A_{horizontal}}$$

Trigonometrically, we can examine 2 complementary triangles and consider the projection of side B onto side C.




To calculate the flux density of solar radiation on the horizontal, we want to project the flux density of radiation associated with the vector C to that normal to the surface, vector A. For the lower triangle and angle β we arrive at:

$$R(i) = R_{\perp} \sin(\beta) = R_{\perp}$$

And for the upper triangle and angle γ we arrive at:

$$R_{\perp} \cos(\gamma) = R_{\perp} \frac{A}{C}$$

The lower the elevation angle, the more the unit area of beam is spread out on the ground, so its flux density on an unit area basis is reduced. As we can see in Fig. 2.14, cos(γ) is one when γ is zero and the sun is directly overhead; cos(γ) is zero when γ is 90 degrees and the sun is aligned with the horizon.

## 2.8 Sun–Earth geometry

The earth rotates on its axis and it revolves around the sun in an elliptical orbit. The area swept by the earth–sun radius is constant, as predicted by Kepler’s Law of Planetary Motion. To perform calculations associated with the flux density of solar radiation on flat and inclined surfaces and its penetration into plant canopy, we must be able to evaluate the angle of the sun from any position on earth at any time of the day. Such a calculation involves computing the angle between a vector normal to a specified point on earth and a projection from the sun. This computation is complicated by the fact that the earth rotates on its polar axis once a day and the earth revolves around the sun once a year.

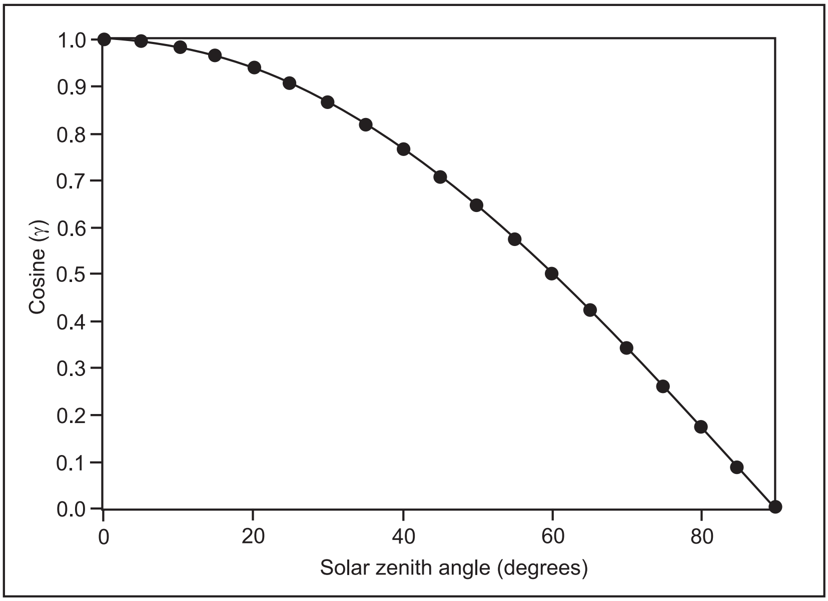



**Figure 2.14** Cosine of solar zenith angle. Values vary non-linearly between 1 and zero

To compute the sun's elevation with respect to the horizon (or its complement, the angle with to the zenith) and its azimuth angle we apply concepts derived from three-dimensional geometry. The important coordinates to know include:

1. Time of day.
2. Longitude.
3. Latitude ($\lambda$).
4. Earth's declination angle ($\delta$).

One way to think about the problem is to try and solve for the angle between two vectors. One is the normal to the earth at a given position and the other is the vector between the point on earth that is normal to the view () and the vector that points to the sun (). From vector analysis we know that the cosine of the vectors is related to their dot product:

$$\vec{a}.\vec{b} = |\vec{a}||\vec{b}| \cos \gamma$$

A schematic of the situation we are interested shows three vectors, $\vec{n}$ S , and S n - , , , and , which represent the vector equal to the radius of the earth and directed toward the surface zenith, the vector from the center of the earth to the sun, and the resultant vector.

It is the angle between the resultant vector and the vector pointing towards the zenith that gives us the angle we desire (Fig. 2.15).

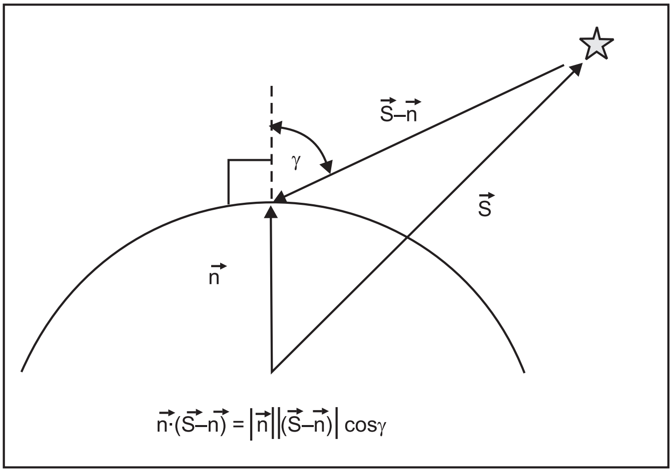



**Figure 2.15** Vectors describing the angle between the sun and a point on earth

In spherical coordinates, we define three directional variables:

$$z = r \cos \gamma$$
$$x = r \sin \gamma \cos \varphi$$
$$y = r \sin \gamma \sin \varphi$$

where, $\gamma$ is the zenith angle and $\varphi$ is the azimuth angle. These angles are for an earth-centred perspective.

In vector notation we define:

$$\vec{S} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \begin{bmatrix} r_s \sin \gamma_s \cos \varphi_s \\ r_s \sin \gamma_s \sin \varphi_s \\ r_s \cos \gamma_s \end{bmatrix}$$

$$\vec{n} = \begin{bmatrix} r_e \sin \gamma_e \cos \varphi_e \\ r_e \sin \gamma_e \sin \varphi_e \\ r_e \cos \gamma_e \end{bmatrix}$$

Remember:

$$\vec{a}\,.\,\vec{S} = a_x S_x + a_y S_y + a_z S_z$$

$$\vec{a}\,.\,\vec{S} = \vec{S}\,.\,\vec{n}$$

$$\left|\vec{a}\right| = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

and a triangle with vertices at A, B and C:

$$\overrightarrow{AB} + \overrightarrow{BC} = \overrightarrow{AC}$$

After much algebraic and trigonometric expansion and substitution we arrive at a new equation of the solar zenith or elevation angles. The cosine of the sun's angle with respect to the zenith (γ) or the sine of the solar elevation angle (β) with respect to the horizontal, can be computed as:

$$\sin(\beta) = \sin(\lambda)\sin(\delta) + \cos(\lambda)\cos(\delta)\cos(h) = \cos(\gamma)$$

λ is latitude and h is the hour angle.

We discuss the components of computing earth–sun angles in more detail.

### 2.8.1 Time of day

The earth is a rotating sphere. The earth rotates around its north-south axis once every 23 hours, 56 minutes and 4 seconds.

It can also be stated that the earth rotates on its axis 2π radians in one day. Over the course of an hour it rotates π/12 radians or 15 degrees. In this framework h is defined as:

Table 2.3 produces values of h and cos(h) for several reference values.

**Table 2.3** The values of h and cos(h) for several reference values.

| Solar time (hour) | h (radians) | Cos(h) |
|---|---|---|
| 6 | 0.5π | 0 |
| 12 | π | –1 |
| 18 | 1.5π | 0 |

In the northern hemisphere, the cosine of π equalling minus one corresponds with the sun being south of an observer at solar noon.

If we are to apply this relation using clock time, then we define h as the fraction of 2π that the earth has turned after local solar noon:

$$h = \frac{\pi}{12}(t - t_0)\ \text{(radians)}$$

$$h = \frac{15\pi}{180}(t - t_0)\ \text{(degrees)}$$

In this instance, t is local time and t0 is solar time.

$$t_0 = 12 - l_c - e_t$$

$l_c$ is the longitudinal correction. Its value is 4 minutes for each degree of longitude east of the standard meridian and is –4 minutes for each degree of longitude west of the standard meridian. Standard meridians possess 15 degree increments from the prime meridian.

The longitude of the Berkeley campus is: 122° W 15′ 47″; latitude is 37° N 52′ 24″. It is about 2.25° west of the standard meridian (120° W), so solar noon occurs about 9 minutes after noon Pacific Standard Time (PST).

The variable, et, represents the equation of time (Fig. 2.16). It arises because of the eccentricity of the earth's orbit around the sun and the obliquity (tilt) of the ecliptic (the great circle that represents the earth's path around the sun). The eccentricity of the earth orbit around the sun forces the angular rotation rate to be variable; this allows equal areas to be swept with time during the earth's orbit. The equation of time (units of hours) is:

$$e_t = \left[ \frac{-104.7\sin(f) + 596.2\sin(2f) + 4.3\sin(4f) - 429.3\cos(f) - 2.0\cos(2f) + 19.3\cos(3f)}{3600} \right]$$

$$f = \frac{\pi}{180}[279.5 + 0.9856d] \qquad [\text{degrees}]$$

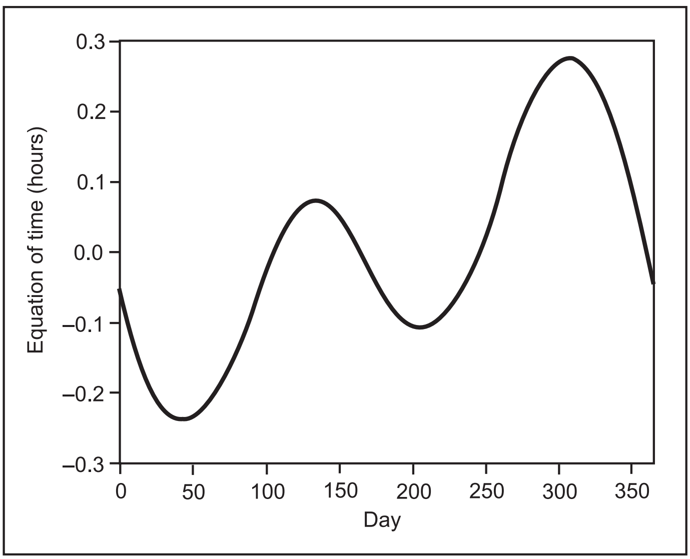



**Figure 2.16** Computations based on the equation of time

d is day number (1 on January 1 and 365 on December 31). Here et and f have units of radians.

The contribution from variation in the orbital speed of the earth to the computation of the sun's zenith angle is not trivial. On February 9, the increment due to the equation of time is 14.2 minutes and on November 6 the contribution is 16.3 minutes.

Sometimes these equations are expressed in terms of Universal Time. In this case, the universal time (Greenwich) is the sum of the true solar time plus and equation for time and the longitudinal time (15 degrees per hour West of Greenwich and –15 degrees per hour East of Greenwich).

### 2.8.2 Longitude

Mariners, navigators and geographers have divided the sphere of the earth in the north–south plane into zones of latitude. They correspond with the degrees of a circle (0 to 360 degrees or 0 to 2π radians). The reference for zero is the prime meridian, near London, at Greenwich, England.

### 2.8.3 Latitude

From an imaginary point at the center of the earth's sphere angular bands of latitude are defined. At the center is the sphere is the equator, defined as zero degrees. Bands of latitude range from zero to 90 degrees for the northern and southern hemispheres.

### 2.8.4 Earth's declination angle

The earth's axis of rotation is tilted 66.5 degrees with respect to its orbital plane around the sun and its axis of rotation is inclined 23.5 degrees from the perpendicular, with respect to this plane. The tilt of the earth affects the angle between the sun beam and the normal over a surface. The sun angle affects the flux density of solar radiation incident on a surface.

The declination angle corresponds with the angle between the sun's rays at solar noon and the equator (Fig. 2.17). The earth's declination angle has limits that correspond with the seasons:

Summer solstice: +23.45 degrees (June 22)

During the summer solstice the sun is directly overhead (90 degrees) at the Tropic of Cancer and has an angle of 66.5 at the Equator and is at the horizon at the Antarctic Circle (66.5 S). Below the Antarctic Circle it is dark 24 hours a day. Above the Arctic Circle (66.6 N) there is sunlight 24 hours a day.

*Equinox:* 0 degrees (March 21 and September 22).

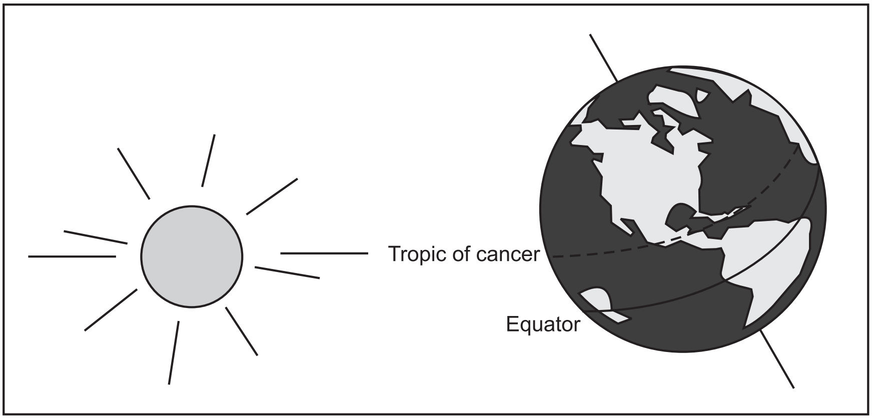



**Figure 2.17** Geometrical configuration between the sun and the earth during the summer solstice

At the Spring and Autumnal Equinox, the sun is positioned over the equator and day length is 12 hours everywhere on earth (Fig. 2.18).

Winter solstice: –23.45 degrees (December 22).

At winter solstice, the sun is directly overhead the Tropic of Cancer (23.5 N) at noon. It is dark 24 hours a day above the Arctic circle (66.5° N) and it is bright below the Antarctic circle for 24 hours (Fig. 2.19). The seasonal changes in the earth–sun geometry are summarised in Fig. 2.20.

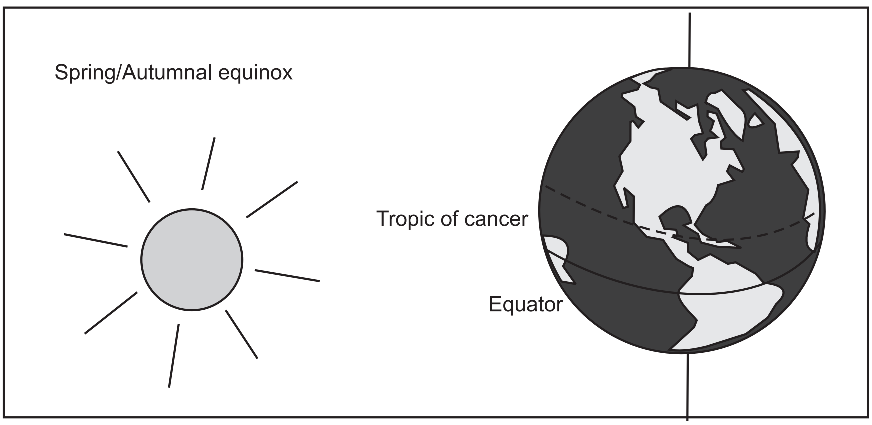



**Figure 2.18** Configuration between the earth and sun during the spring and autumnal equinox

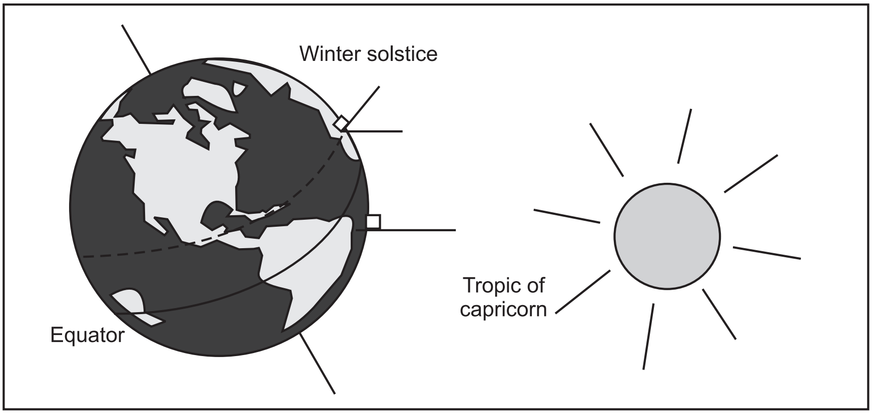



**Figure 2.19** Configuration between the sun and earth during the winter solstice

A mathematical equation for computing the declination angle is:

$$\delta = -23.45 . \cos\left(\frac{360(D+10)}{365}\right) \qquad \text{(degrees)}$$

$$\delta = -23.45 \cos\frac{\pi}{180} . \cos\left(\frac{2\pi(D+10)}{365}\right) \qquad \text{(radians)}$$

where, D is day number [after Jones (1995)]. In this case the declination angle is expressed in terms of degrees. Multiplying by π/180 converts degrees to radians.

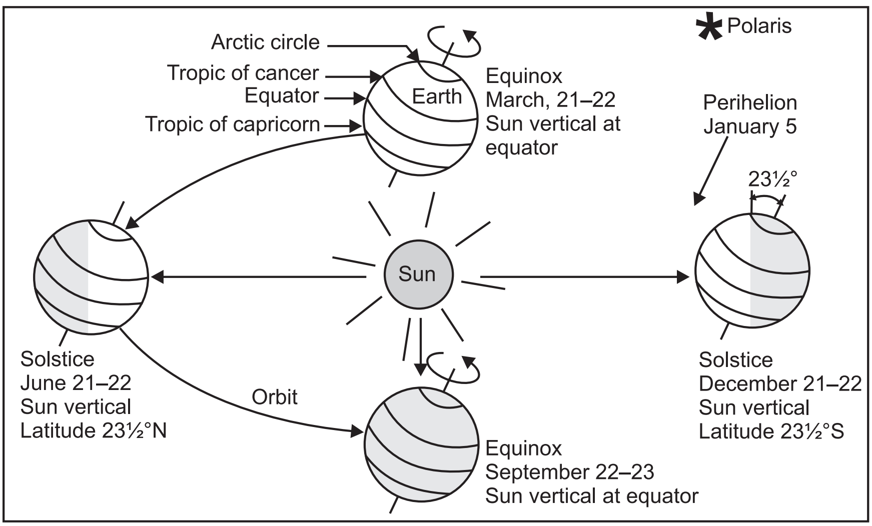



**Figure 2.20** Basic earth–sun geometry

To understand how the declination angle varies with time, geometricians define a celestial sphere, of infinite radius, that rotates around the earth, the center point of the sphere. The intersection between the equatorial plane of the earth with the celestial sphere defines the celestial equator. From the point of view of the celestial sphere, the sun follows on orbit over the course of a year on the ecliptic. It is tilted 23.5 with respect to the celestial equator. Figure 2.21 shows seasonal variation in the declination angle.

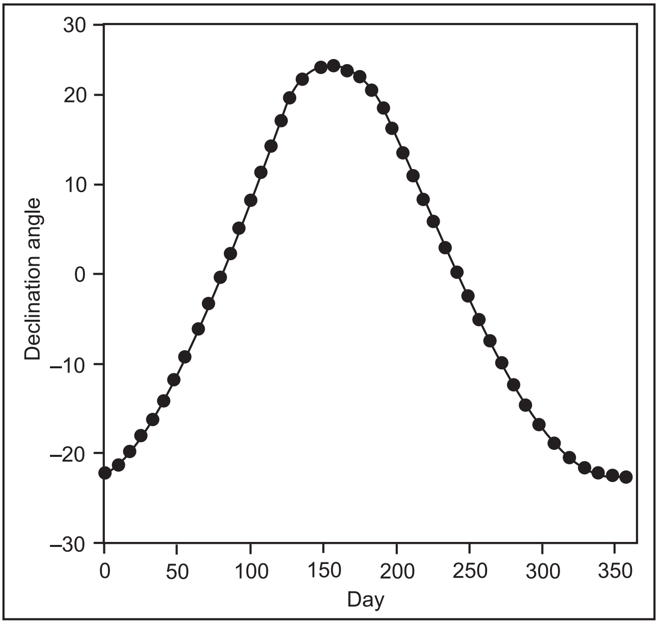



**Figure 2.21** Seasonal variation in the declination angle

The sun's position on the celestial sphere can be estimated by knowing the angle of the right ascension and the declination. The right ascension is the angle between the hour circle of the vernal equinox and the hour circle of the sun (the angle between the sun and the north pole of the celestial sphere).

How azimuth angle is computed depends on the coordinate system which one uses. A mathematical perspective increments angles, starting from due south and rotating counter clockwise, from 0 to 360 degrees. A compass considers true north to be zero and increases angles in a clockwise manner from 0 to 360. An astronomical coordinate system increases azimuth angles from 0 to 180 in the clockwise direction and from 0 to –180 in the counter clockwise direction, starting with south as zero.

Campbell and Norman compute azimuth angle in the mathematical system as a function of the declination and zenith angles and latitude:

$$\cos(Az) = \frac{-\sin\delta - \cos\gamma \sin\lambda}{\cos\lambda \sin\gamma}$$

(east is 90 degrees, north is 180 and west is 270 degrees). Monteith and Unsworth compute solar azimuth, relative to south, as a function of the declination, hour and the zenith angles:

$$\sin(Az) = \frac{-\cos\delta \sin(h')}{\sin\gamma}$$

They define h′ as the hour angle which the earth has turned after local solar noon, as a fraction of 2π, h′ = 2πt/24.

From Oke:

If t <12,

$$\cos(Az) = \frac{\sin\delta\cos\lambda - \cos\delta\sin\lambda\cos h}{\sin\gamma}$$

If t >12,

$$\cos(Az) = 2\pi\frac{\sin\delta\cos\lambda - \cos\delta\sin\lambda\cos h}{\sin\gamma}$$

An illustration of the motion of the sun at a particular location for several times during the year is presented in Fig. 2.22. Of course the sun is the highest at noon and it rises in the east and sets in the west during the equinox. For northerly climes, the sun is perceived to rise in the northeast and set in the northwest during the summer. And if we sit above the Arctic circle, the sun will revolve around the horizon during the summer.

We can manipulate this equation of the solar elevation angle to compute the times of sunrise and sunset, too.

The time of sunrise and sunset occur when the solar elevation angle is zero (or the zenith angle is π/2). It is a function of the latitude of the site and the earth's declination angle:

$$\cos(h) = -\tan\lambda\tan\delta$$

$$t_{sunrise} - t_{12} - \frac{h}{15}$$

$$t_{sunset} - t_{12} - \frac{h}{15}$$

The length of the day is $t_{sunrise}$ minus $t_{sunset}$, which equals 2h/15.

$$2t = \frac{24}{\pi}\cos^{-1}(\tan\lambda\tan\delta)$$

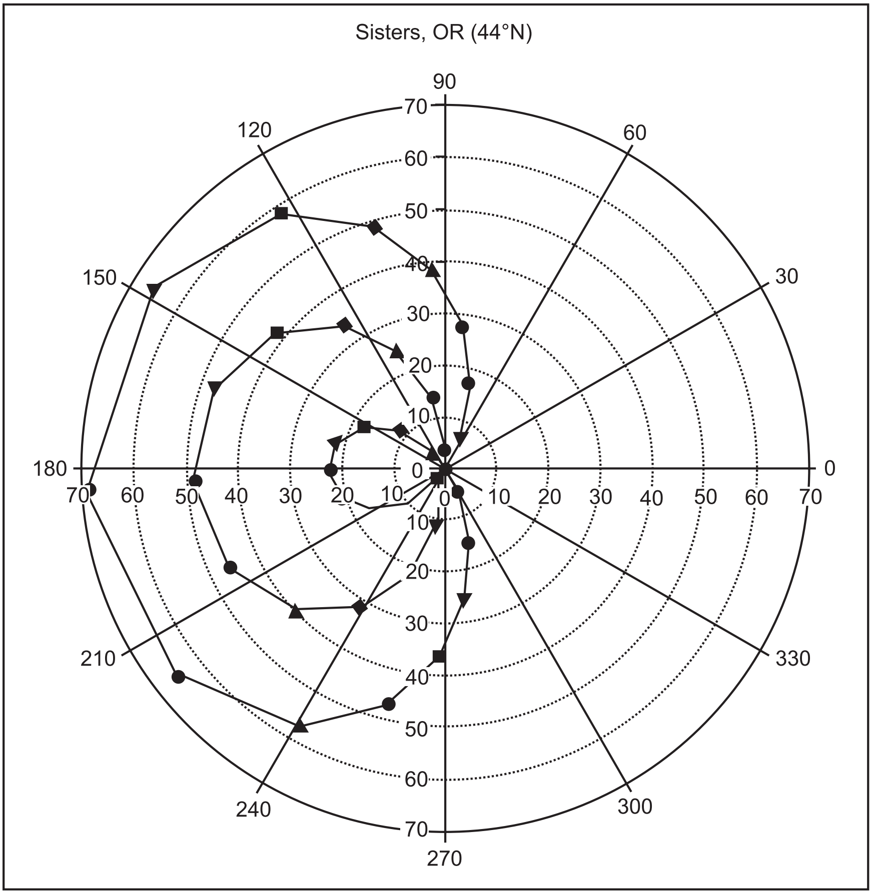



**Figure 2.22** Solar elevation and azimuth angles at Sisters, OR (44° N) for summer and winter solstices and the equinoxes

Numerous algorithms are now available on the worldwide-web for computing solar elevation angles over the course of a day or year for any position on the earth. One source of information on solar elevation angles is giving at: http://susdesign.com/sunangle/

It has been updated since 2000 and is easy to use.

### 2.8.5 View factors

View factors are important for they give us information on the projected area of various geometry shades. The ratio of the area of shadow cast on the horizontal (Ah) and the area projected in the direction of the beam (A) yields information on the relation between the mean flux density and the horizontal flux density.

$$A_pS_p = (Ah \sin \beta)S_p = A_hS_b$$

If the area of the object is A then:

$$\bar{S}_b = \frac{A_h}{A} S_b$$

The shape factor is denoted by $A_h/A$. For the case of a sphere, we know that it projects a circle with an area of $\pi r_2$. The shadow projected onto the ground from a beam source is:

$$\frac{\pi r^2}{\sin\beta}$$

The surface area of a sphere is:

$$4\pi r_2$$

This yields the shape factor:

$$\frac{A_h}{A} = \frac{\pi r^2}{4\pi r^2 \sin\beta} = \frac{1}{4\cos\gamma}$$

Geometry of a projected sphere are shown in Fig. 2.23.

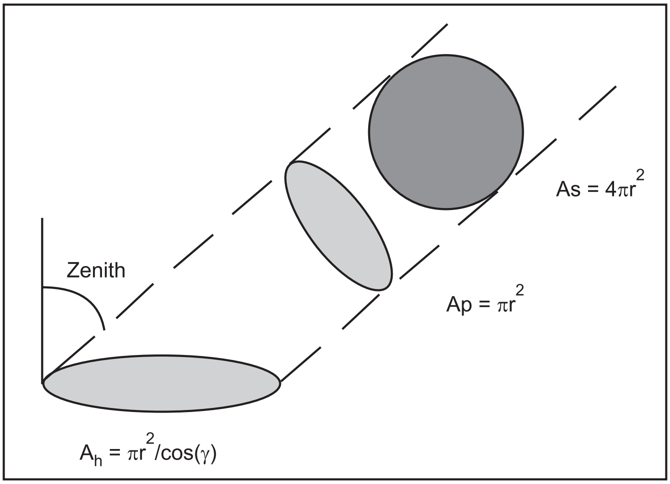



**Figure 2.23** Geometry of a projected sphere

*Cone:*

$$\frac{A_h}{A} = \frac{(\pi - \theta_0)\cos\alpha + \sin\alpha \cot\beta \sin\theta_0}{\pi(1 + \cos\alpha)}$$

Inclined plane (Fig. 2.24):
$Ah = \sin\alpha \cot\beta - \cos\alpha$

## 2.9 Radiation on inclined surfaces, mountain slopes

The earth is not flat. Ecosystems exist on sides of hills that may face east, west, south or north. The amount of direct sunlight incident on the side of a hill will depend on the angle between the sun's beam and the angle normal to the slope.

Direct solar radiation flux density on an inclined surface:

$$R(i) = R_{\perp} \cos(i)$$

R(i) is the radiation normal to an inclined surface.

$R_{\perp}$ is the radiation flux density normal to the sun's rays.

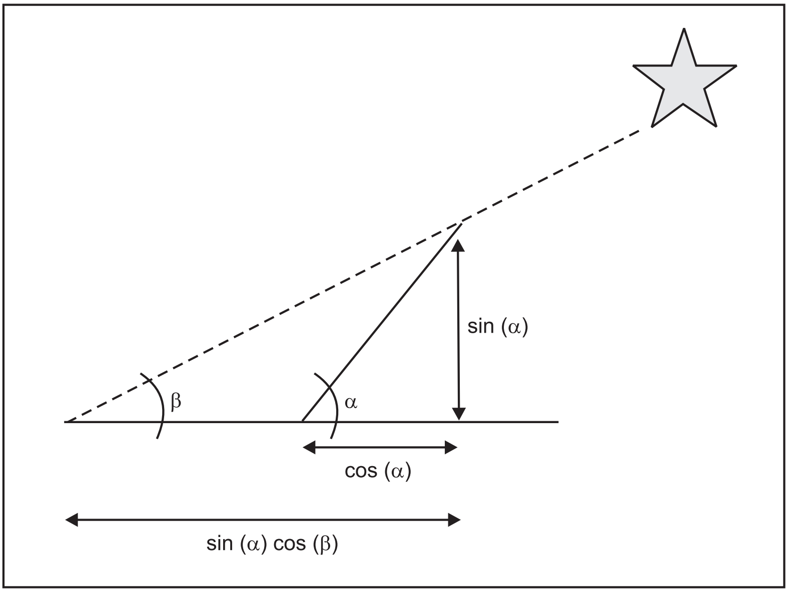



**Figure 2.24** Projection of inclined plane on a surface

The angle of incidence on any given surface is computed as:

$$\cos(i) = \cos\alpha \sin\beta + \sin\alpha \cos\beta \cos\Psi$$

α is the angle of the inclination of the surface relative to a horizontal plane.

β is the solar elevation angle.

Ψ is the difference between the sun's azimuth angle and the azimuth angle of the project normal to the surface on the horizontal.

Alternatively this equation can be expressed in terms of the sun's zenith angle (γ), where $(\gamma + \beta) = \pi/2$:

$$\cos(i) = \cos\alpha\cos\gamma + \sin\alpha\sin\gamma\cos\Psi$$

Angle between any surface and the sun:

$$\cos\xi = [\sin\lambda\cos(h)(-\cos\alpha\sin\chi) - \sin(h)(\sin\alpha\sin\chi) + (\cos\lambda\cos(h))\cos c]\cos\delta + [\cos\lambda(\cos\alpha\sin\chi) + \sin\lambda\cos c]\sin\delta$$

ξ is the angle between the sun and the surface normal.

χ is the zenith angle of the slope.

α is the azimuth angle of the slope.

# 3
# Solar devices

## 3.1 Introduction

This chapter discusses solar devices such as solar photovoltaic modules, silicon solar cells, silicon wafers, solar lanterns, solar street lighting and solar home lighting systems, solar powered fans, solar air coolers and air conditioners, solar refrigerators, solar cooking systems, solar televisions, solar water pumps and solar water heater, etc. The use of solar energy has already made a mark in our lives and there is much more to come very soon.

## 3.2 Solar panels

Solar panels, generally comprising of arrays of photovoltaic cells, use the solar energy directly from the sun to generate electricity for our daily use. Being environment friendly in nature, solar panels collect the solar energy which is available in abundance on our planet and convert it using the advanced technology developed by human beings. This invention of humans has led to a great achievement in world's history of conserving non-renewable resources and saving the planet as well as the natural resources from depletion.

This concept is already famous in countries like Australia, United Kingdom and United States of America, etc. and is becoming very popular in solar panels India market as well. Even used solar panels are being used in these countries so that the installation cost reduces further and it is easy for the people to generate green energy. A large number of factories in the solar panels India market are now using solar panels for their daily electricity usage (Fig. 3.1).

They make optimal use of renewable energy from the sun and are very much environmental friendly in nature. Manufacturing solar panels is not an easy process. With the advancement of photovoltaic devices, we have seen a significant increase in the number of solar panels manufacturers all over India. The solar panels manufacturers manufacture the solar panels by first cutting the ingots, which are generally cylindrical in shape, into circular disc shaped silicon wafers. The silicon wafers are very carefully cut using saws or other cutting devices. These are then carefully cleaned to remove any impurities which might have arisen in the cutting process. After the cleaning process is completed, the silicon wafers are then polished and metal conductors and the products for doping the wafers for the desired electrical properties are put on each silicon wafer module. The modules are then placed on a flat sheet of solar panel and are spread in a matrix or a grid structure on the sheet. The solar panels are then installed on the roof tops or top of the buildings to get the maximum solar energy from the sun in order to run as expected.

**Figure 3.1** Solar panels

We all know of global warming issues happening all over the world. This has also been proved by the rise in the earth's mean temperature and a significant increase in the natural calamities impacting the whole world. In such a critical situation, the use of alternate forms of energy like hydro energy, wind energy, solar energy, etc. are really appreciated and also encouraged by the governments in different parts of the worlds. The increased usage of solar products such as solar panels, solar water heaters, solar air coolers and the upcoming of various solar power plants has been an intelligent effort to fight global warming issues. Simple products like solar panels for generating the electricity for homes and offices, solar lighting for lighting up the homes, offices and streets, solar heaters for heating waters and swimming pools, solar cells to run small devices, etc. are really useful to prevent the global warming issues and they even do not consume any non-renewable resources of the earth.

## 3.3 Silicon wafers

A silicon wafer is a thin slice of crystal semiconductor, such as a material made up from silicon crystal, which is circular in shape. Silicon wafers are made up of pure and single crystalline material. They are used in the manufacture of semiconductor devices, integrated circuits and other small devices. There are multiple processes through which silicon wafers are manufactured. One such process which is widely used by most of the silicon wafers manufacturers is the Czochralski Growth process.

### 3.3.1 Silicon wafers manufacturing process

Ingots, made up of silicon which is very pure, are cast into cylindrical shapes. This is done by pulling the seed crystal from a molden melt. The ingots are then cut, using saws or other cutting devices, in thin circular shapes which result in formation of silicon wafers. The wafers, hence created, are thoroughly cleaned after this process to remove the impurities and are also properly shaped to increase their efficiency. Once the cleaning and shaping up of the silicon wafers is done, they can then be doped so that they acquire the electronics technicalities as desired by the silicon wafers manufacturers. This process takes a lot of time and efforts and due care must be taken in each and every stage of this process to ensure the accurate results. Silicon wafers are available in different sizes and dimensions as desired by the silicon wafers manufacturers.

Silicon wafers have amazing mechanical and electrical properties and due to the same reason, they are the most widely used wafers in the industry today. They capture a huge portion of the market and are able to satisfy almost all of the needs of their customers. One of the majorly used products in which they are used are silicon solar cells which are now very popular all over the world.

## 3.4 Solar cells

Solar cells are semi-conductor devices which use sunlight to produce electricity. They are manufactured and processed in a similar fashion as computer memory chips. Solar cells are primarily made up of silicon which absorbs the photons emitted by sun’s rays. The process was discovered as early as 1839. Silicon wafers are doped and the electrical contacts are put in place to connect each solar cell to another. The resulting silicon disks are given an anti-reflective coating. This coating protects sunlight loss. The solar cells are then encapsulated and placed in an aluminium frame. The process requires continuous monitoring to ensure quality control over a period of time. After the manufacturing process is complete they undergo final test to check their efficiency under normal conditions (Fig. 3.2).

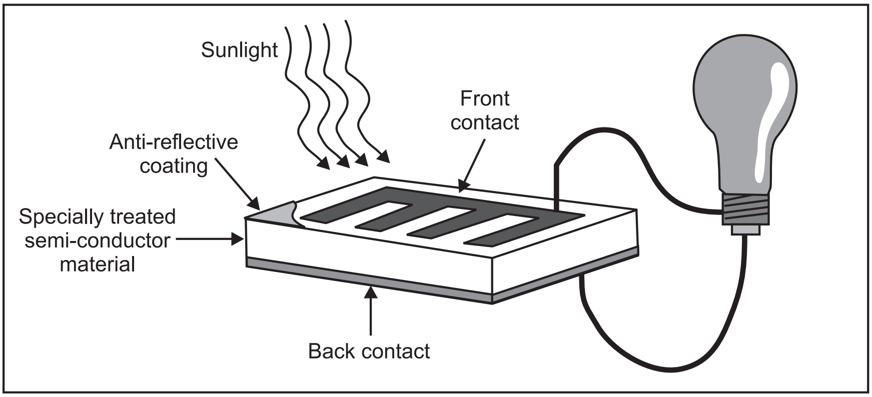



**Figure 3.2** Solar cells

Solar cells provide more energy than other conventional sources with an additional advantage of being light weight and cost effective. Developing cheaper alternatives to solar cells such as amorphous silicon and polycrystalline silicon are also in the pipeline. Current research reveals that in order to increase the amount of sunlight effectively used and focusing it, prismatic lenses and layers of different materials could also be used.

## 3.5 Solar lanterns

Solar photovoltaic lantern is basically a portable lighting device suitable for either indoor or outdoor lighting covering a full range of 36°. The lantern can be used for 3 hours/day with autonomy of 2 days. Solar PV lantern consists of:

1. 7W CFL lamp
2. Sealed maintenance free battery
3. Electronics
4. Solar PV module
5. Module mounting structure
6. Interconnecting cable

The battery, lamp and the electronics are placed inside portable ABS plastic housing. Solar PV module generates electricity when exposed to direct sunlight, thus exploiting the unlimited source of free energy. A PV module consists of several small solar cells made of semiconductor material. Each of these solar cells generates a DC voltage and are capable of producing a finite amount of current. These solar cells are connected in series to form a PV module and are terminated to a terminal block for external connections (Fig. 3.3).

**Figure 3.3** Solar lanterns

The system has been designed to meet the following requirements: The PV module has to be mounted external to the building on rooftop with maximum exposure of solar cells to the sunlight. Mounting frame provided may be used for fixing the module in position.

Compact fluorescent lamps also known as CFL are energy saving and the most efficient lamps. Due to the nature of their construction, these lamps generate higher light (lumens) output for a given amount of power or in other words these lamps consume less amount of power when compared to other lamps for a given light output. In the solar lantern, sealed lead acid maintenance free rechargeable batteries are used. The complete electronics basically consists of two functions:

1. Battery charge controller to protect deep discharging and overcharging of the battery. Suitable circuits have been provided to continuously monitor the battery voltage and based on preset voltage levels prevent either overcharging of the battery or deep discharging. Circuits for providing visual indication to indicate battery state of charge are also provided.
2. Inverter to generate the recommended AC voltage to the CFL and to ensure proper ignition and subsequent glow of the lamp. The inverter converts DC battery voltage to AC, which is fed to the lamp. Suitable filtering circuits are provided to ensure as good a sine wave as possible across the lamp.

## 3.6 Solar lights

Sun is the driving force behind everything. Solar lights, too, are backed up by the sun's energy. Solar lights are basically those lights that work without batteries. They get charged up by the sun's energy in the day time and then they light up in the dark. These lights consist of an LED (light emitting diode) and a photovoltaic solar panel. The photovoltaic panel directly converts the sun's energy into electricity that lights up the LED. There is a light sensitive switch inside these lights that makes them light up, the minute it begins to get dark (Fig. 3.4).

**Figure 3.4** Solar lights

Solar lights are used in various areas nowadays. They are being used in the gardens to bring out the beauty of the landscape. They are used near swimming pools to light up the pathways. Solar lights are even being used to light up the streets. These lights are not expensive to install and neither do they have any maintenance cost attached to them. It uses the sun's energy for free of cost to run itself. They do not need anyone to start and stop it. They work automatically and are one of the best means to conserve power. Solar lights work on solar energy, which is a renewable source of energy. In this day and age, when the fossil fuels are getting exhausted at a very high rate for power generation purposes, solar lights come as the saving grace for humans. These lights help in saving power for the future generations and they are very eco-friendly. Solar lights are quite convenient and hassle free to install. They do not require wires in their installation and can light up to 8–10 hours.

Solar lights are being improved upon with each passing day. The solar technology being utilised in them is the technology of tomorrow. When nothing will be left on earth to create power from, humans will turn to sun only. Solar lights work on cloudy days as well if there's enough sun's energy stored in them. Researchers and scientists are working to improve this technology only, so that people can get the best out of these lights on cloudy and rainy days as well. Solar lights are very versatile in nature. Since they do not require any cords and extensions, they can be placed about anywhere, be it on the ground, on the wall, patios or fences.

These lights are available in many stylish designs and sizes. They are quite an attractive item to decorate the house, besides being very useful. The light emitted by these lights depends on the number of light emitting diodes placed in them. People can choose the amount of lighting they want, depending on the design of the solar lights they opt for. Solar lights are a good option to go with. They help people cut down their electricity bills and also help in making their houses more eye-catching with their elegant looks. These lights are available in different designs to suit the household needs and various colours like brown, copper, white, black and antique finish, etc.

## 3.7 Solar lighting systems

With the passage of each single day, the importance of saving power for the future generations is being realised by every individual. Measures are being taken up to save the fossil fuels from getting depleted, as they are non-renewable source of energy. Solar lighting systems are one of the measures to utilise the unbound sun's energy. Solar lighting systems work on simple basics, i.e. they trap the solar energy and convert it into electricity that lights up the LED present inside them, when there is darkness. Solar lighting systems have photovoltaic modules integrated in them that convert the solar energy directly into electricity (Fig. 3.5).

These solar lighting systems are very handy and easy to install. There are no extensions or wires required to install them. They can be placed about anywhere, from wall, fences, grounds, patios, anywhere. All it needs is to be placed in direct sunlight, so that it gets recharged in the day time and lights up during the night. There's a variety of solar lighting systems available in the market today. It all depends on the customer's requirements, as to what kind of solar lighting systems they want to set up in their house.

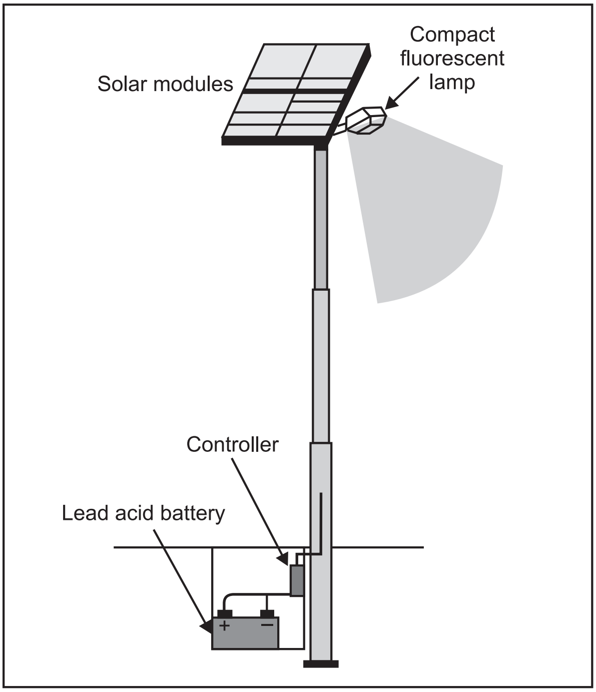



**Figure 3.5** Solar lighting systems

Solar lighting systems differ in design, colour and the amount of lighting they provide. They also vary in their working systems. There are some solar lighting systems that light up automatically, after a certain point, when the light gets diminished. There are other types which have motion sensors positioned in them, that makes them light up the minute when there is some motion detected in a certain amount of radius. Then, there is another type of solar lighting systems that have a manual switch attached to it. Finally, there are some that are time monitored, i.e. they light up for a set time period according to the user's needs. Solar lighting systems are being used in different areas because of its versatility. Motion sensor solar lights are mounted in the households for security reasons. Light sensitive solar lights are placed in the gardens to add to its beauty and light up the pathways during the nights, without any extra cost. Solar lighting systems are being used in the shop signs, which get charged up during the day and light up during the night. Traffic signal lights are one of the best places that are utilising the solar energy. They are better than those lights that run on unreliable batteries. It helps in saving a huge amount of government's money as they are powered by the free source, sun. Solar lighting systems are also being applied in the bus stands, parking lots and streets lights. All these places are always under the sun and to make the best use of sun's energy here is a wise decision.

Solar lights are cost effective, hassle free and do not have any maintenance cost. Solar panels are the answer to the energy problems of the present as well as the future. The solar lighting systems help the people in going green, who want to save the nature for future.

## 3.8 Solar street lights

In this day and age, when the energy resources are being wasted every single second, it has become important for the people to go green. Solar street lights are a step taken up in that direction only. These lights do not run on conventional power, but are run by the solar energy. Solar street lights are the invention of the latest technology. They help in reducing the electricity consumption of any country, dramatically. They are worth every single penny that goes in its installation. Installation cost is the only cost, which the government has to bear, rest it does not call for any maintenance (Fig. 3.6).

**Figure 3.6** Solar street systems

Solar street lights are economically viable and are being put to use in most of the developing countries. Change has begun in the right direction with the increase in use of these lights. Solar street lights do not require any excavation or any huge amount of labour work in their installation, as there are no cables attached to them. They have solar panels affixed to them that get charged by the sunlight and that makes them light up during the night. These panels must be properly aligned in the right direction, so that they can collect as much sunlight as possible. The operation of solar street lights, from dusk to dawn, is controlled by the photocell integrated within them.

Solar street lights are getting popular by day because they make the roads safe at night at a very effective cost. Basically, the general public pays the taxes for such services, and when there will be no cost attached to the street lights working, automatically the taxes will lower down. It is a win-win situation for both the public and the environment, as it does not work on the power of fossil fuels. Another major advantage of solar street lights is that they work in any condition whether there's power or not. For example, after any natural calamity, like a storm, hurricane or a blizzard, many lights get damaged and they do not work because the power lines fail. But these lights work, because of sun's natural power and they help in safeguarding the streets at night in a horrendous moment like the one aforesaid.

Solar street lights have lower power consumption and higher power efficacy. These lights have a longer lifetime as well when compared to conventional street lights. Solar street lights can work up to 50,000 hours, if there's no major damage done to them. These lights do not require a regular maintenance; all they need is a regular check up to see if everything is working optimally.

Solar street lights are no doubt the lights of the future. They are getting accepted by the day, by all the countries because of their numerous advantages for the earth. Street lights are a necessity of every country and going solar with these lights, will definitely have a huge impact in the conservation of power. That day is not far away, when every street in the world will be lit up by the solar street lights and every country will go green with its usage.

## 3.9 Solar ingots

Solar ingots are materials that can be cast into different shapes so that they can further be processed to make solar products like silicon solar cells, silicon wafers, etc. In the manufacturing of silicon wafers, solar ingots, which are formed of silicon which is very pure in nature, are cast into cylindrical shapes for further processing. The solar ingots are then cut, using saws or other cutting devices, in thin circular shapes which result in formation of silicon wafers. Using the solar ingots, the silicon wafers, which are prepared so far, are then thoroughly cleaned to remove the impurities and are also properly shaped to increase their efficiency.

There are many reasons why solar products should be used as a cleaner and more efficient source of energy. It becomes imperative to save on the manufacturing costs of solar ingots, silicon wafers and silicon solar cells so that their market price is very cheap and a lot of people use them in their daily lives.

There has also been an increase in the use of solar ingots and other solar products like solar water heaters, solar panels, silicon wafers, etc. in the last decade. To increase the growth rate of such products and hence their daily use, various new furnaces as well as new crystallisation processes have been developed in due course of time.

We hope that there will be a significant increase in the number of solar products which are being sold in each and every country.

## 3.10 Solar attic fans

These fans work on solar energy through solar panels and do not require any conventional power. Solar attic fans have photovoltaic modules incorporated in them, which convert the sun's light directly into electricity that powers the motor of the fan. The main function of solar attic fans is to reduce the temperature of the attics that can rise up to 160°F.

In the summers, when the sun shines in its full glory, the temperature of the attics rises up and that heat gets transferred to the entire house. That time an air conditioner is put to best use and the electricity bills touches the ceilings. Solar fans helps in venting out the hot air from the attics and thus reducing the workload on the air conditioners. These fans are not just about the summers; they are very beneficial during the winters as well. When the snow get accumulated on the roof of the house, the heat trapped in the attic makes that snow melt and hence, creates a puddle surrounding the entire house. Solar fans exhaust the trapped heat and prevent such happening.

Solar attic fans run the fastest when the sun shines the strongest, thereby keeping the overall temperature of the house neutral all year round, be it hot or cold. These fans even prevent the growth of mildew and moulds in the attic due to the moisture that gathers up in the attic, owing to the household activities like cooking, washing, showering, etc. Solar fans aerate this moisture and protect the wooden attic structure. Solar fans have no maintenance or operating cost attached to it. They do not even require any installation cost. You don't need any electrician to install these fans in your attic. You can do it yourself, very easily. You just need to put a hole in the drywall and install it in there. Solar fans are cost-effective and they have a very long lifespan.

Solar fans are available in three styles: The gable fan, the curb mounted fan and the self flashing roof fan. The first one exhausts the air horizontally through the gable end of the roof. The second type gets attached over a curb that is appended to the roof and the third type is affixed directly to the roof because the fan base is flat.

Solar fans are godsend to humans in this day and age, when global warming is happening at an unbelievable rate. Not only they help in lowering down the house temperature, they make use of the renewable source of energy. Utilising the solar energy to its full potential is one step forward towards a green and healthy future. Saving the electricity and in turn the power, with these fans, will surely help the future generations to see some amount of beautiful earth that is present today.

## 3.11 Solar water pumps

Water is the lifeline of every human being; without it, there's nothing. But there are places where there's a huge problem of water. The unavailability of water in remote places is causing the death of millions. To solve this problem, solar water pumps have been invented. Poor people do not have the money to run their households, so there's no way that they can afford a conventional grid-tied water pump to suffice their water needs. Even if they are able to afford the initial installation cost of the pump, it's impossible to match up with its running cost. Solar water pumps come as a saving grace for these poor souls, who desperately need help to meet their water requirements.

Solar water pumps run on solar energy. They are more eco-friendly and economical in their operation than the pumps powered by an internal combustion engine. The conventional water pumps operate on gas and diesel for their powering, which is a very expensive affair. Water pumps are generally used for irrigation purposes and farmers cannot afford such expensive pumps for their needs. Solar water pumps are an ideal solution for them. They only cost the installation charges and after that they work free on the solar energy. Solar water pumps are very easy to install and use. They do not even require extensive chords to power them. All they need is just a solar panel, which has photovoltaic modules included in it that convert the sun's energy into electricity. Solar water pumps are very eco-friendly, as there is no pollution caused by them. They help in preventing the global warming and cut down the electricity bills to bare minimum.

Solar water pumps helps in bringing water to the remote places, specially the desert areas where there is scarcity of water and abundance of solar heat. It is the ideal place to install solar water pumps. Besides that, solar water pumps are becoming popular among the home owners as well. They install the solar water pumps to irrigate their gardens and nurseries. Having a huge garden and maintaining it is not an easy task. It requires regular watering and for that, one needs a constant supply of water. To get that constant supply of water would obviously cost a lot.

Hence, solar water pumps come as a boon for such people. Solar energy is the best renewable source of energy that will help in prevention of the exhaustion of the fossil fuels. Solar water pumps are one of the various means to harness the sun's energy in most efficient manner. These pumps are an ideal solution in this age, to save the earth from this over increasing pollution. They are one of the best ways to help out the masses, who can't afford high electricity bills just to quench their thirst. Various countries, around the globe, are opting for these pumps because of their numerous benefits for the people as well as the environment. Solar pumps are used principally for three applications:

1. Village water supply
2. Livestock watering
3. Irrigation

A solar pump for village water supply is shown schematically in Fig. 3.7. The village will have a constant water demand although there is need to store water for periods of low insolation (low solar radiation). In environments where rainy seasons occur some of this demand can be met by rainwater harvesting during the rainy season.

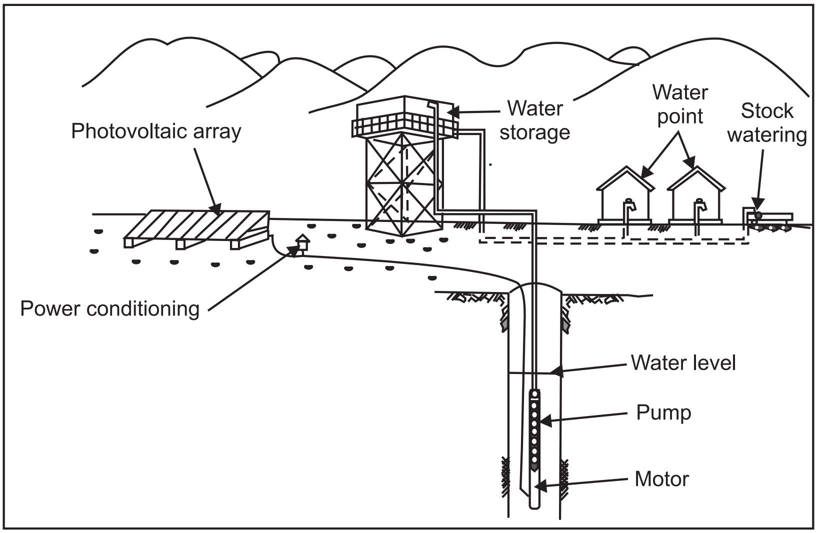



**Figure 3.7** Village water supply

Ideally in Sahelian Africa the storage would be 3–5 days of water demand. In practice some installed tanks do not have sufficient capacity and are smaller than a days demand leaving the tank empty at the end of the day. This is due to a mismatch between the sizing, pump capacity and the demand profile during the day. The main applications for solar water pumping are for livestock watering in the USA and Australia. In Africa the systems are used for village water systems and livestock watering. While applications of solar water pumping for irrigation are on the increase especially in India and China. A solar irrigation system (Fig. 3.8) needs to take account of the fact that demand for irrigation water will vary throughout the year. Peak demand during the irrigation seasons is often more than twice the average demand. This means that solar pumps for irrigation can be under-utilised for most of the year although there can be a reduction in strength of the sun during these times reducing supply side of the equation. Attention should be paid to the system of water distribution and application to the crops. The system should minimise water losses, without imposing significant additional head on the pumping system and be of low cost.

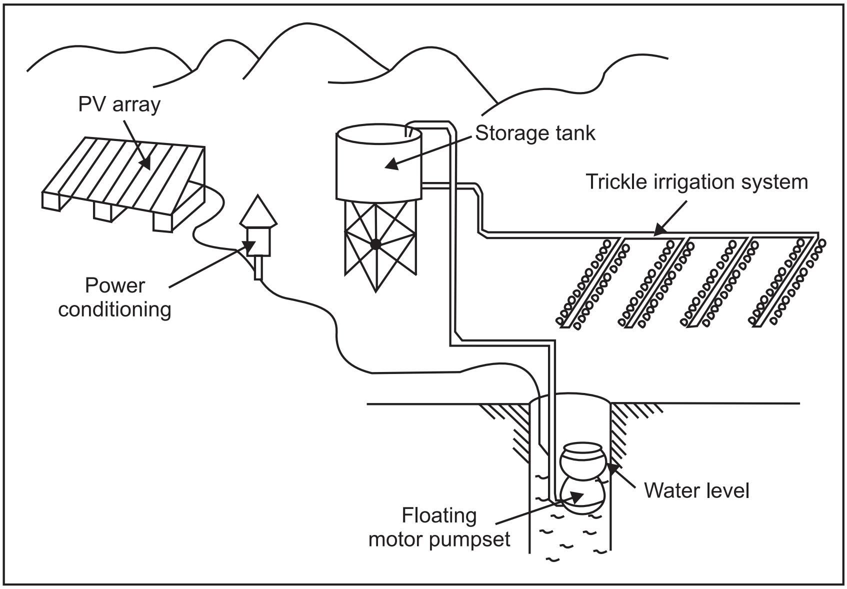



**Figure 3.8** Solar irrigation system

Photovoltaic pumps are made up of a number of components. There is a photovoltaic array which converts solar energy directly into electricity as DC. The pump will have an electric motor to drive it. The characteristics of these components need to be matched to get the best performance. The pump motor unit will have its own optimum speed and load depending on the type and size of the pump.

## 3.12 Solar water heater

We can use sun's energy in a lot of ways for our benefit. Solar powered products like solar water heaters help us achieve this potential at no cost at all.

*Process steam generation:* The systems can be used to support almost any kind of thermal load for industrial or commercial applications, including:

1. Steam generation
2. Process hot water production
3. Desalination
4. Industrial and domestic hot water heating
5. Food processing (washing, cleaning, cooking, etc.)

Let us understand the make up of a solar water heater. The solar energy gets accumulated with the help of a collector. It consists of a solar panel with a selected coating that absorbs the heat and transfers it to the riser pipes underneath it. The temperature of the water being circulated in the pipes rises up and gets stored up in a tank. The storage tank is insulated to maintain the temperature of the water (Fig. 3.9).

The climate of a region and location are the deciding factors in choosing the solar water heater suitable for your use. Warmer areas benefit from active systems with direct circulation whereas colder climates require indirect circulation which makes use of a heat transfer fluid. For rooftops you can install passive systems where city water pushes the heated water to the outlet and storage is the collector itself. One can also go for the thermosiphon system where the storage tank is placed above the collector and gravity pushes the heated water.

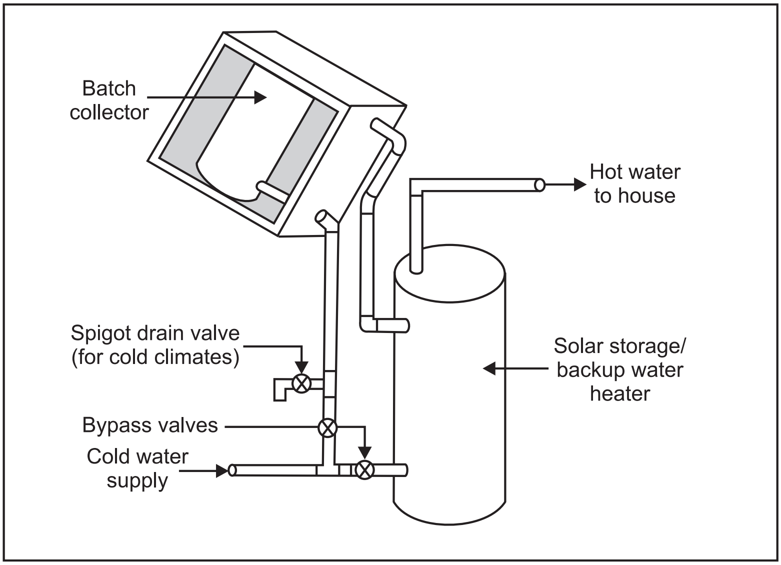



**Figure 3.9** Solar water heater

Changing weather condition, limitation of space, amount of sunlight available or the capacity are some other factors that can influence your choice for buying a solar water heater.

### 3.12.1 Types of solar water heaters

Other types of a solar water heater are the flat plate collectors and evacuated tube collectors.

(a) *Flat plate collectors:* Flat plate collectors have glass on top and have blackened metallic absorbers inside and riser tubes to carry water.

(b) *Evacuated tube collectors:* Evacuated tube collectors are made of a glass tube where the outer covering absorbs the solar radiation and the heat generated is transferred to the flowing water.

After taking a look at the types of a solar water heater available in the market, one can decide which one would be best suitable for their homes. Similarly, during summers, one can choose from solar air conditioners and solar coolers. It is an excellent option for saving your electricity bills by 50–80 per cent and approximately 1500 units of electricity annually over the other conventional water heating alternatives like geysers of a capacity of 100 litres. Not only domestic but solar water heater is also used for commercial purposes such as hotels, hospitals, industries, dairies and enjoys a wider international market now. One of the major advantages of solar water heaters is that they are non-polluting and prevent the emission of carbon dioxide to a large extent. Once you have got your solar water heater installed, you can stop worrying about the return on investment.

## 3.13 Solar refrigerators

Solar refrigerators are not something that will come into existence in the future and will be invented in the developed countries, for that matter. Solar refrigerators are already in existence and were developed in the developing countries where there's always a shortage of power supply and excess of poverty. When one thinks of the word 'solar', photovoltaic modules and panels automatically come to mind, that converts the sunlight into electricity but that is not the case here. Solar refrigerators work on the evaporative cooling system. They just need sunlight and some water for their functioning. Solar panels in India are now being manufactured on a large scale. This has helped a lot in the popularity of solar refrigerators in India.

Solar refrigerators are an invention of necessity. In poverty-stricken developing countries, where there is no power and no money, usage of conventional refrigerators is out of the question. To start with, people cannot afford to buy such refrigerators and secondly, they cannot maintain such grid-power based refrigerators because of no regular supply of power. Thus, for such people an alternative was desperately required and that led to solar refrigerators. Solar refrigerators operate on the solar energy that cost not a single penny to the user. The main reason to build such refrigerators is to protect the perishable foods like meat and dairy items from getting spoiled as well as prevent the spoilage of the vaccines. These refrigerators are widely popular in many countries of Africa like Namibia and Zambia.

Solar refrigerators are very easy to make. They basically work on the principle of heat conduction and convection. There are two cylinders in solar refrigerators; the inner cylinder can be made of any recycled metal and it is placed inside the outside cylinder, which can be made of anything available in the household, like cardboard, plastic or wood. The outer cylinder must have holes on it, so that the sunlight can reach inside for its powering. The gap between the two cylinders is packed with organic material, either sand or wool and it is then saturated with water. The perishable items are kept inside the inner cylinder and then the whole set up is placed in direct sunlight. The heat of the sun evaporates the water in the organic material. This heat, in effect pulls the heat from the inner chamber and that leads to the cooling and reduction in temperature up to 6°C.

In the present age, conventional refrigerators prove to be very harmful for the environment. The chlorofluorocarbons present in the refrigerators contribute to global warming and ozone depletion. Using solar energy to power the solar refrigerators, aids in minimising the destructive impacts of conventional refrigerators on the environment. Hence, solar refrigerators are not only an economical solution to the problems of billions of people but it is also, one of the ways to safeguard the mother earth from complete destruction. Solar refrigerators can help us to protect the nature, so that even the future generations are able to see what we can see right now. It is in our hands to create a better future and the first step towards it can be the usage of solar refrigerators.

## 3.14 Solar televisions (TV)

Television has been called names like idiot box, since forever. The reason behind this is the addictiveness, which it impinges on the human brain. People get addicted to it because of its alluring programs and cannot seem to switch it off. Televisions around the globe consume the most power supply as they are turned on almost 24×7. This leads to sky-scraping electricity bills and wastage of the non-renewable energy. Solar televisions come as a solution to all the problems, which a traditional television puts up for the populace.

Solar televisions are not just a myth anymore; they have been invented in countries like Japan. Solar televisions are not run by grid-power and this is its biggest advantage. There are still, many places around the globe where power supply has not been made possible. Solar televisions are the answer to the prayers of those people living there. Living in the third world countries with no power supply is not a happy picture. Without the television, it is impossible for those people to know about what is happening around the world. Solar televisions run on solar power and thus can be accessed from anywhere. People will only gain from solar televisions; there is no doubt about that.

Solar televisions operate due to the thin-film photovoltaic panel that is attached to the television set. This solar panel traps the sun's energy and turns it into electricity. This electricity, in effect then powers the television. Solar televisions have very low power consumption. These televisions utilise less than one-third of the total energy required by traditional CRT-televisions. The area of the solar panel attached to them, is about the same as of the television screen.

Solar televisions are the creation of a futurist mind. The person who has invented these amazing televisions has surely thought about the future. Everyone knows that future is not far off, when all the non-renewable sources of energy will get completely used up. There will be no power to run the numerous inventions, which man has invented so arduously. There will be no more refrigerators, televisions, air conditioners, blenders, etc. because there will be no electricity to power them.

Hence, we need to start thinking about the alternatives and solar power is the most effective and beneficial alternative to power the various appliances. Solar televisions, thus, are the alternatives to help the future generation. These televisions are not popular right now but the scientists are working day and night to improve these solar televisions, so that they are used ubiquitously. They will not only help in saving the energy for the future but they will also help the present generation to lower their electricity bills. Thus, choose the right way. Go solar with solar televisions.

## 3.15 Solar coolers

During the summers, the sun shines in its full glory over our heads and makes us sweat like pigs. This results in the extra consumption of electricity to power our air conditioners and our coolers. Electricity bills touch the ceilings during the summers because of 24 hours of usage. But now, this can be warded off by making use of solar coolers. Solar coolers are just like conventional water coolers. The only difference between the two is that, the former operates on the DC power produced by the solar panels and the latter one operates on AC power.

The best quality about the solar coolers is that they can be made out of any conventional water cooler and still costs only 1/4 to 1/3 of power consumption of conventional units. It is an able decision to make use of solar power to run the water coolers because it is due to the sun only that their need arose in the first place. Making the optimum use of solar power during the daytime to power up the solar coolers would surely help in saving of a lot of electricity thereby putting off the burden from the electricity bills. During the night time, the solar coolers can be run by the battery backup that stores the solar power during the daytime. This makes the solar coolers function 24/7 and serves as a feasible alternative for the humans (Fig. 3.10).

Solar coolers are very easy to make from any conventional water cooler. To make a solar cooler, attach a 12 V automobile radiator fan and a bilge pump to the traditional cooler. The original fan and motor need not be removed for the purpose. The radiator fan can be mounted in front of the squirrel cage fan present in the water cooler. The bilge pump, too, can be placed next to the original pump inside the cooler. Conventional water coolers run on 110 V of AC power, whereas the solar cooler runs on a 12 V solar panel attached to it. The solar electric panel can be mounted on the home made tracker, which helps in extending the time period of solar cooler's working. It has been noticed that almost 2 to 3 hours of extra usage is possible with the tracker.

Solar coolers are very economical and to get the best out of them. One must switch it on since early morning when the sun comes out. Ideally, an AC or a cooler is turned on when it begins to get really hot. But with solar coolers, it would not cost a penny to start them since early morning. It will be put to maximum utilisation and will keep the house temperature at about 15 degrees.

Solar coolers work best in dry climate areas. They are eco-friendly and do not add to the unlimited pollution already surmounting the earth. Solar coolers help in preserving the priceless non-renewable sources of energy, which goes to waste in an unrestricted manner during the summers. Going solar with solar coolers is the coolest decision one can take for themselves as well as for the environment.

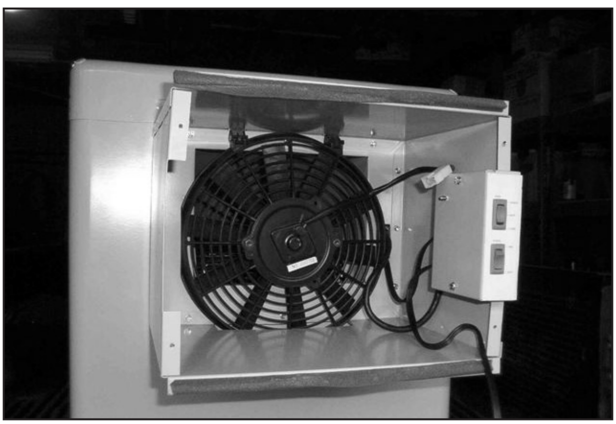


**Figure 3.10** Solar coolers

## 3.16 Solar air conditioners (AC)

In this day and age, when there is a rapid decease in the fossil fuels and a swift increase in pollution happening, going Green is a wise decision. Solar air conditioners are one of the best ways of contributing to the nature's preservation. During the summers, when the heat of the sun surpasses all the boundaries and creates inhospitable conditions for the humans, an air conditioner is turned on to seek relief. Conventional air conditioners use excessive power and add to the electricity bills tremendously. During the summers, an air conditioner is a necessity of every household. In today's world, one can't stop using them but one can always go solar with them.

Solar air conditioners work on the power of sunlight. The more the sunlight, the more effective the solar air conditioner would be. Solar air conditioners are a practical appliance and are getting popular by the day. People, now value the power of solar energy and they appreciate the solar products being launched in the market. Solar air conditioners help the populace to get relieved of the summer temperature in a guilt free manner. Conventional air conditioners have harmful elements in them like chlorofluorocarbons, which contribute excessively to global warming and the expansion of the ozone hole. Solar air conditioners, on the other hand are totally free of such hazardous elements. They run on electricity, which is produced by the photovoltaic integrated on the solar panel attached to the solar air conditioners. This power is absolutely free of cost and does not add to any electricity bill, either. Solar air conditioners work on renewable energy resource and thus aid in the conservation of the non-renewable resources.

Solar air conditioners have many other benefits as well. If you install solar air conditioners in your home, you will get great incentives by the government on its installation cost. The savings, which one generates by using solar air conditioners, would even enhance their property rates. Solar air conditioners are very silent, have no compressor appended to it and hence have no costly maintenance. It is just the solar panels, which require a timely check up to ensure optimum sunlight absorption during the daytime.

Solar air conditioners are used as an alternative to conventional air conditioners in countries like Japan, China and India. There the electricity price is very high and to avoid heavy electricity bills, going solar is the safest bet. These air conditioners are proving to be, one of the finest invention by man kind as they cut back the electric bills to 1/3 of the original. They provide the same amount of cooling, which a traditional air conditioner does. The chief difference between the two conditioners is that, the air produced by the solar air conditioners is 100 per cent eco-friendly. It helps the humans as well as the environment to breathe healthily. Solar power is the power of the future. Getting access to solar power, as fast as one can, is the smart thing to do because future is not far-off. The time has come to make the better judgement yourself.

## 3.17 Solar cooking systems

Cooking food is a necessity of every household. You cannot stop cooking, no matter how much concern you have for the preservation of the resources. You cannot stop using gas, until and unless you have a better substitute. Solar cooking systems are those alternatives, which will help you to cook food efficiently and conserve the energy resources for the future. Employment of LPG for cooking, leads to the wastage of non-renewable resources. It is a very dangerous gas as well, since it ignites immediately. If left unopened, gas would spread very rapidly and would set fire to the entire house, in matter of seconds. It just needs a spark to get ignited (Fig. 3.11).

**Figure 3.11** Solar cooking system

Solar cooking systems are altogether different from conventional gas systems in all its aspects. Solar cooking systems do not work on any kind of gas, so there is no chance of wastage of any resources. They do not operate on the burning of wood either, so there is no chance of deforestation. Solar cooking systems work on solar energy. They just require sunlight to cook food and nothing else. It is hence clear, that these cooking systems do not cost a single penny to the pocket as they function using the free energy source. Solar cooking systems are very eco-friendly and do not assist in any kind of pollution, global warming or ozone layer depletion, for that matter.

Solar cooking systems are basically solar cookers, solar kettles, solar bowls and hybrid solar grills, that are used to cook food. Solar cooking systems essentially work on a simple rule of converting the light energy into heat energy. Reflective mirrors are used in the solar cookers to converge the sunrays to a single focus point, where they produce heat. At this point the food is kept and hence gets cooked.

There is a variety of solar cookers available in the market nowadays. Some of the most popular solar cookers are parabolic cookers, panel cookers and box cookers. Solar kettles are mainly used to boil water using the solar glass tube technology that stores solar energy, and powers the kettle. Hybrid solar grills have moveable grill surface, which has an adjustable parabolic reflector balanced on a tripod. This parabolic reflector reflects the sunrays and converge them to grill food.

All around the globe, solar cooking systems are being promoted because of their various advantages for the environment. Third world countries are endorsing these solar cooking systems because they do not require any gas or electricity for their functioning. Solar cooking systems are an answer to the woes of poverty-stricken people living in remote areas, who depend on wood for cooking their food. These people won't have to go to the forests anymore to gather wood and they won't even have to get their throats choked due to the fumes coming out of wood's combustion. Solar cooking systems and solar panels are gaining acceptability among the masses due to their utilitarian aspect as well as their contribution to the conservation of the natural resources.

## 3.18 Solar steam generators

In present time, the excessive use of electricity for every small thing has led to a shortage all around the globe. Resources are getting exhausted swiftly and population is increasing on the double. This situation is heading towards a disastrous end and to avert that end solar steam generators have been invented. Solar steam generators utilise the solar energy to produce electricity rather than the conventional non-renewable resources. Traditionally, electricity is produced in power plants by the turning of heavy turbines, which are powered by steam produced by the burning of coal, gas or oil. Hence, these power plants emits out unsafe gases in the atmosphere that is causing the global warming.

Solar steam generators are extremely eco-friendly and helps in keeping the air clean and produce maximum electricity. These generators' popularity is increasing by the day around the sphere, as they work on a renewable source of energy, i.e. solar thermal energy. Another factor for increasing acceptability of solar steam generators is that solar energy is absolutely free whereas the price of coal and oil is escalating by the minute.

Solar steam generators consist of a boiler, heliostats, heat transfer fluid and steam turbine. Boiler is the place where the heat is collected from the sun. The spherical mirrors (heliostats) used in the solar steam generators can either be cylindrical parabola or the circular parabola. The former one focuses the sunlight to a line whereas the latter one focuses it to a point. Heliostats, the moveable parabolic mirrors, face automatically towards the sun to absorb the heat of the optimally. The heat transfer fluid can either be water or liquid sodium. When the fluid placed inside the boiler gets heated up by the sun's heat, it is transferred to the heat exchanger where it gets transformed into steam. Water's temperature can be raised up to 220°C using the solar steam generators. After 100°C, water converts into steam under very high pressure and this steam is then pushed on to the steam turbine. The pressure of the steam makes it to move in circular motions and thus creates electricity (Fig. 3.12).

Solar steam generators' utility is helping people to get access to electricity where there is extreme shortage of it. In distant future, when there will be no more fossil fuels to burn that can power the turbine, solar steam generators will be the only solution. Solar steam generators help in protecting the environment as well as the human species from harmful diseases, which are caused due to the deadly fumes and gases released by the conventional power plants. Using solar steam generators from today itself is a step taken towards a secure future. Safeguarding oneself from utter despair, when there will be no more resources to burn, is the only priority in everyone's mind right now. Solar steam generators are being adopted by responsible countries across the globe, which understand the value of non-renewable resources and the harmful effects of their sheer wastage.

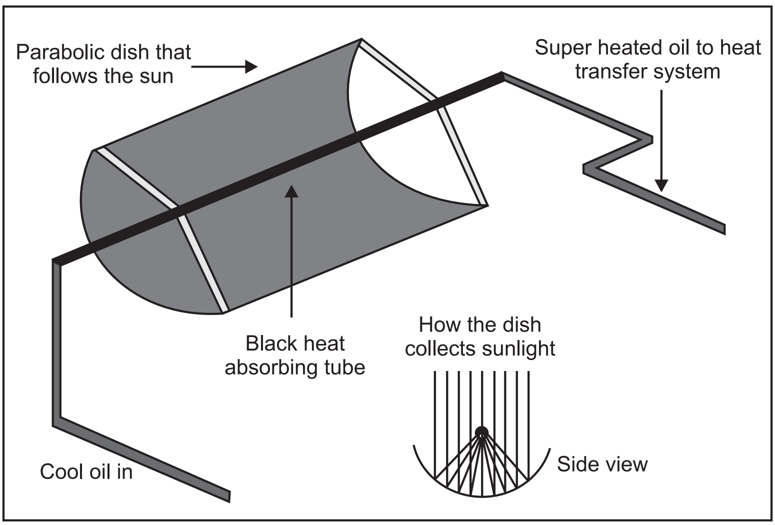



**Figure 3.12** Solar steam generators

## 3.19 Solar flat-plate collectors

Solar energy is the most viable source of power, which is gaining popularity by the day. Heating the water using the solar energy is one of the most efficient utilisation of solar power. Basically, in solar heating systems there are solar flat-plate collectors and storage tanks to store the thermal water. Solar flat-plate collectors are one of the types of solar collectors that are used to absorb and intercept the sun's radiations for water heating. Thermal water obtained using the solar flat-plate collectors is generally used in the hotels, businesses, homes, swimming pools, under floor heating, etc.

Solar flat-plate collectors are the solar thermal collectors that consist of an insulated and weatherproof box, which has a black metal absorber sheet and built in pipes where the water is present. The water inside the pipes gets heated up by the solar energy and by natural convection the water circulates through the system. There are chiefly two types of solar heating—active and passive. In passive solar water heating, the hot water from the solar collectors gets transferred to the storage tanks through means of gravity. The motion of water is slow compared to the demand of the water supply. But when there are some electrical pumps attached in the system to push the thermal water from the collector pipes to the storage tanks then it becomes an active solar heating system. Solar flat-plate collectors are varied in design but mainly all of them contain a flat-plate collector, a transparent cover and a heat transport fluid (generally water or an antifreeze fluid). Flat-plate collector absorbs the sunrays and the transparent cover lets the solar energy to pass through reducing the heat loss from the absorber. The heat transport fluid that circulates in the pipes affixed to the collector removes the heat from the absorber and heats the water, which is then transferred to the storage tanks. Solar flat plate collectors, best suit the demand of places where the required water temperature ranges 30° to 70°C. Solar flat-plate collectors are the best alternative to the conventional geysers used in the winters to heat the water. The electricity consumption that reaches its peak using the power-grid geysers can be cut back to 20 per cent consumption with the installation of solar flat-plate collectors in any household. The solar flat plate collectors are now designed very diligently for areas where freezing is a possibility. They are plumbed in such a way that the water gets drained down completely using gravity, so that their cracking does not happen due to freezing.

Solar flat-plate collectors are being installed everywhere nowadays because of their utilitarian aspect as well as their economical aspect. They do not use grid-tied power, and hence, do not cause any wastage of the natural resources. Solar-flat plate collectors work on free solar power and are thus aiding the prevention of global warming. Solar-flat plate collectors utilise the solar power optimally to heat the water and hence meet all the needs of humans all year round.

A flat-plate collector is shown in Fig. 3.13. The basic parts noted are a full-aperture absorber, transparent or translucent cover sheets, and an insulated box. The absorber is usually a sheet of high-thermal-conductivity metal with tubes or ducts either integral or attached. Its surface is painted or coated to maximise radiant energy absorption and in some cases to minimise radiant emission. The cover sheets, called glazing, let sunlight pass through to the absorber but insulate the space above the absorber to prohibit cool air from flowing into this space. The insulated box provides structure and sealing and reduces heat loss from the back or sides of the collector.

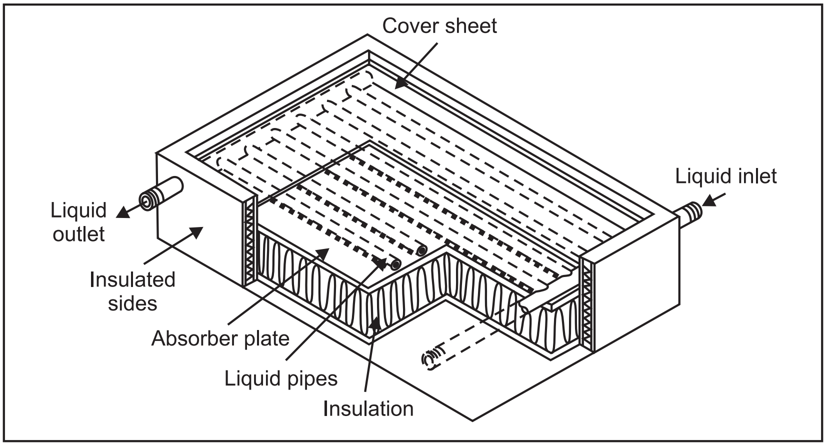



**Figure 3.13** A typical liquid flat-plate collector

## 3.20 Solar power plants

Sun is the ultimate source of energy for each and every living thing on earth. Harnessing sun's unbound energy to the best of its ability is done in solar power plants. There are many ways to get the power from the sun through solar panels in solar power plants. There are direct as well as indirect ways to convert the sun's heat into power. Directly, the heat from sun is converted into electricity using photovoltaic. Indirectly, the sun's heat is converted into power by concentrating the heat of the sun to boil the water and then the steam from it is used for electricity generation (Fig. 3.14). The construction of solar power plants is the best thing that is happening right now for the future generations. With each passing day, the consumption of power, which is produced by burning of the fossil fuels, is increasing at a very high rate. Fossil fuels are getting depleted at a much faster rate than they are being produced. If things keep on going the way they are right now, that time is not far away when there will be no energy or power to consume. To prevent this dreadful day from coming into being, solar power plants are being set up around the globe. These solar power plants have proved to be and still are a boon to mankind.

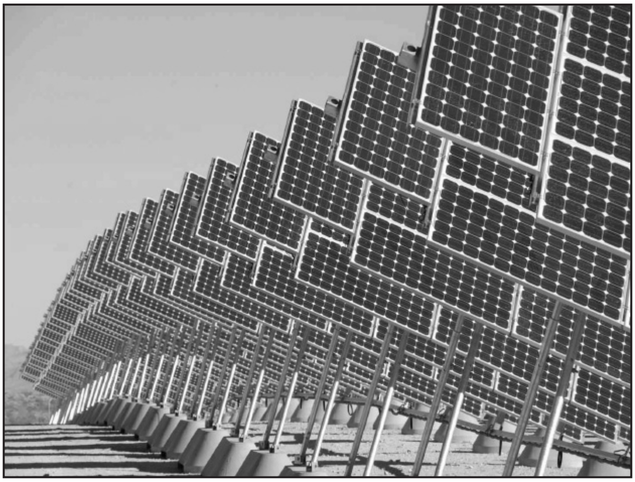


**Figure 3.14** Solar power plants

Sun's radiations are intermittent and to get a continuous supply of power various methods are adopted at the solar power plants. One of such ways taken on at the solar power plants is storage. The solar power is produced by concentrating the sun's radiations, with the help of mirrors and lenses, into a single beam and that beam is used to heat the water. The steam from the hot water is then used in a conventional power plant to generate electricity. This produced electricity is then stored so that it can be utilised when the sun is not there outside, shining in its full glory. Although the solar power plants are expensive to install, in spite of that, countries around the globe are opting for solar power plants instead of other power plants because solar energy is a renewable source of energy. This solar energy when combined with the other sources of energy such as the wind, biomass and hydro power, results in 100 per cent renewable energy. This has been accomplished in a large combined power plant, which is bigger than any of the solar power plants, set up in Germany. Solar power plants are the best source of power supply not only for the humans but for the environment as well. Solar energy is very eco-friendly and it does not contribute towards global warming at all as the other fossil fuel power plants do. Solar power plants make the ideal utilisation of sun's energy and are helping the future generations from being powerless. Solar power plants are a like a ray of hope for the human race to survive when all the fossil fuels will get exhausted and there will be nothing left to produce power from anymore.

# 4
# Solar thermal energy

## 4.1 Introduction

Solar thermal energy (STE) is a technology for harnessing solar energy for thermal energy (heat). Solar thermal collectors are classified as Low-, medium- or High-temperature collectors. Low temperature collectors are flat-plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat-plates but are used for heating water or air for residential and commercial use. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production. STE is different from (and indeed much more efficient than) photovoltaics, which converts solar energy directly into electricity.

## 4.2 Low-temperature collectors

Low-temperature collectors are generally installed to heat swimming pools, although they can also be used for space heating. Collectors can use air or water as the medium to transfer the heat to their destination.

### 4.2.1 Heating, cooling and ventilation

In the United States, heating, ventilation, and air conditioning (HVAC) systems account for over 25 per cent (4.75 EJ) of the energy used in commercial buildings and nearly half (10.1 EJ) of the energy used in residential buildings. Solar heating, cooling, and ventilation technologies can be used to offset a portion of this energy.

Thermal mass materials store solar energy during the day and release this energy during cooler periods. Common thermal mass materials include stone, concrete, and water. The proportion and placement of thermal mass should consider several factors such as climate, day lighting and shading conditions. When properly incorporated, thermal mass can passively maintain comfortable temperatures while reducing energy consumption. A solar chimney (or thermal chimney) is a passive solar ventilation system composed of a hollow thermal mass connecting the interior and exterior of a building. As the chimney warms, the air inside is heated causing an updraft that pulls air through the building. These systems have been in use since Roman times and remain common in the Middle East.

Solar space heating with solar air heat collectors is more popular in the USA and Canada than heating with solar liquid collectors since most buildings already have a ventilation system for heating and cooling. The two main types of solar air panels are glazed and unglazed. Glazed solar collectors are designed primarily for space heating and they re-circulate building air through a solar air panel where the air is heated and then directed back into the building. These solar space heating systems require at least two penetrations into the building and only perform when the air in the solar collector is warmer than the building room temperature. Most glazed collectors are used in the residential sector.

Unglazed solar collectors are primarily used to pre-heat make-up ventilation air in commercial, industrial and institutional buildings with a high ventilation load. They turn building walls or sections of walls into low cost, high performance, unglazed solar collectors. Also called, ‘transpired solar panels’, they employ a painted perforated metal solar heat absorber that also serves as the exterior wall surface of the building. Heat conducts from the absorber surface to the thermal boundary layer of air 1 mm thick on the outside of the absorber and to air that passes behind the absorber. The boundary layer of air is drawn into a nearby perforation before the heat can escape by convection to the outside air. The heated air is then drawn from behind the absorber plate into the building’s ventilation system.

A Trombe wall is a passive solar heating and ventilation system consisting of an air channel sandwiched between a window and a sun-facing thermal mass. During the ventilation cycle, sunlight stores heat in the thermal mass and warms the air channel causing circulation through vents at the top and bottom of the wall. During the heating cycle the Trombe wall radiates stored heat.

Solar roof ponds are unique solar heating and cooling systems developed by Harold Hay in the 1960s. A basic system consists of a roof-mounted water bladder with a moveable insulating cover. This system can control heat exchange between interior and exterior environments by covering and uncovering the bladder between night and day. When heating is a concern the bladder is uncovered during the day allowing sunlight to warm the water bladder and store heat for evening use. When cooling is a concern the covered bladder draws heat from the building’s interior during the day and is uncovered at night to radiate heat to the cooler atmosphere. The Skytherm house in Atascadero, California, uses a prototype roof pond for heating and cooling.

Active solar cooling can be achieved via absorption refrigeration cycles, desiccant cycles, and solar mechanical processes. In 1878, Auguste Mouchout pioneered solar cooling by making ice using a solar steam engine attached to a refrigeration device. Thermal mass, smart windows and shading methods can also be used to provide cooling. The leaves of deciduous trees provide natural shade during the summer while the bare limbs allow light and warmth into a building during the winter. The water content of trees will also help moderate local temperatures.

### *Process heat*

Solar process heating systems are designed to provide large quantities of hot water or space heating for non-residential buildings. Evaporation ponds are shallow ponds that concentrate dissolved solids through evaporation. The use of evaporation ponds to obtain salt from sea water is one of the oldest applications of solar energy. Modern uses include concentrating brine solutions used in leach mining and removing dissolved solids from waste streams. Altogether, evaporation ponds represent one of the largest commercial applications of solar energy in use today.

Unglazed transpired collectors (UTC) are perforated sun-facing walls used for preheating ventilation air. UTCs can raise the incoming air temperature up to 22°C and deliver outlet temperatures of 45–60°C. The short payback period of transpired collectors (3 to 12 years) make them a more cost-effective alternative to glazed collection systems. As of 2009, over 1500 systems with a combined collector area of 3,00,000 $m^2$ had been installed worldwide. Representatives include an 860 $m^2$ collector in Costa Rica used for drying coffee beans and a 1300 $m^2$ collector in Coimbatore, India used for drying marigolds.

A food processing facility in Modesto, California uses parabolic troughs to produce steam used in the manufacturing process. The 5000 $m^2$ collector area is expected to provide 4.3 GJ per year.

## 4.3 Medium-temperature collectors

These collectors could be used to produce approximately 50 per cent and more of the hot water needed for residential and commercial use in the United States. In the United States 30 per cent of the system qualifies for a federal tax credit + additional state credit exists in about half of the states. Labour for a simple open loop system in southern climates can take 3–5 hours for the installation and 4–6 hours in Northern areas. Northern system requires more collector area and more complex plumbing to protect the collector from freezing. With this incentive, the payback time for a typical household is four to nine years, depending on the state. Similar subsidies exist in parts of Europe. A crew of one solar plumber and two assistants with minimal training can install a system per day. Thermosiphon installation have negligible maintenance costs (costs rise if antifreeze and mains power are used for circulation) and in the US reduces a household's operating costs by $6 per person per month. Solar water heating can reduce $CO_2$ emissions of a family of four by 1 ton/year (if replacing natural gas) or 3 ton/year (if replacing electricity). Medium-temperature installations can use any of several designs: Common designs are pressurised glycol, drain back, batch systems and newer low pressure freeze tolerant systems using polymer pipes containing water with photovoltaic pumping. European and International standards are being reviewed to accommodate innovations in design and operation of medium temperature collectors. Operational innovations include 'permanently wetted collector' operation. This innovation reduces or even eliminates the occurrence of no-flow high-temperature stresses called stagnation which would otherwise reduce the life expectancy of collectors.

### 4.3.1 Solar drying

Solar thermal energy can be useful for drying wood for construction and wood fuels such as wood chips for combustion. Solar is also used for food products such as fruits, grains, and fish. Crop drying by solar means is environmentally friendly as well as cost effective while improving the quality. The less money it takes to make a product, the less it can be sold for, pleasing both the buyers and the sellers. Technologies in solar drying include ultra low cost pumped transpired plate air collectors based on black fabrics. Solar thermal energy is helpful in the process of drying products such as wood chips and other forms of biomass by raising the heat while allowing air to pass through and get rid of the moisture.

### 4.3.2 Cooking

Solar cookers use sunlight for cooking, drying and pasteurisation. Solar cooking offsets fuel costs, reduces demand for fuel or firewood, and improves air quality by reducing or removing a source of smoke. The simplest type of solar cooker is the box cooker first built by Horace de Saussure in 1767. A basic box cooker consists of an insulated container with a transparent lid. These cookers can be used effectively with partially overcast skies and will typically reach temperatures of 50–100°C.

Concentrating solar cookers use reflectors to concentrate light on a cooking container. The most common reflector geometries are flat-plate,

disc and parabolic trough type. These designs cook faster and at higher temperatures (up to 350°C) but require direct light to function properly.
The Solar Kitchen in Auroville, India, uses a unique concentrating technology known as the solar bowl. Contrary to conventional tracking reflector/fixed receiver systems, the solar bowl uses a fixed spherical reflector with a receiver which tracks the focus of light as the sun moves across the sky. The solar bowl's receiver reaches temperature of 150°C that is used to produce steam that helps cook 2000 daily meals.

Many other solar kitchens in India use another unique concentrating technology known as the Scheffler reflector. This technology was first developed by Wolfgang Scheffler in 1986. A Scheffler reflector is a parabolic dish that uses single axis tracking to follow the sun's daily course. These reflectors have a flexible reflective surface that is able to change its curvature to adjust to seasonal variations in the incident angle of sunlight. Scheffler reflectors have the advantage of having a fixed focal point which improves the ease of cooking and are able to reach temperatures of 450°–650°C. Built in 1999, the world's largest Scheffler reflector system in Abu Road, Rajasthan India is capable of cooking up to 35,000 meals a day. By early 2008, over 2000 large cookers of the Scheffler design had been built worldwide.

### 4.3.3 Distillation

Solar stills can be used to make drinking water in areas where clean water is not common. Solar distillation is necessary in these situations to provide people with purified water. Solar energy heats up the water in the still. The water then evaporates and condenses on the bottom of the covering glass.

## 4.4 High-temperature collectors

Where temperatures below about 95°C are sufficient, as for space heating, flat-plate collectors of the non-concentrating type are generally used. Because of the relatively high heat losses through the glazing, flat plate collectors will not reach temperatures much above 200°C even when the heat transfer fluid is stagnant. Such temperatures are too low for efficient conversion to electricity.

The efficiency of heat engines increases with the temperature of the heat source. To achieve this in solar thermal energy plants, solar radiation is concentrated by mirrors or lenses to obtain higher temperatures—a technique called concentrated solar power (CSP). The practical effect of high efficiencies is to reduce the plant's collector size and total land use per unit power generated, reducing the environmental impacts of a power plant as well as its expense.

As the temperature increases, different forms of conversion become practical. Up to 600°C, steam turbines, standard technology, have efficiency up to 41 per cent. Above 600°C, gas turbines can be more efficient. Higher temperatures are problematic because different materials and techniques are needed. One proposal for very high temperatures is to use liquid fluoride salts operating between 700°C and 800°C, using multi-stage turbine systems to achieve 50 per cent or more thermal efficiencies. The higher operating temperatures permit the plant to use higher-temperature dry heat exchangers for its thermal exhaust, reducing the plant's water use–critical in the deserts where large solar plants are practical. High temperatures also make heat storage more efficient, because more watt-hours are stored per unit of fluid.

Since the CSP plant generates heat first of all, it can store the heat before conversion to electricity. With current technology, storage of heat is much cheaper and more efficient than storage of electricity. In this way, the CSP plant can produce electricity day and night. If the CSP site has predictable solar radiation, then the CSP plant becomes a reliable power plant. Reliability can further be improved by installing a back-up system that uses fossil energy. The back-up system can reuse most of the CSP plant, which decreases the cost of the back-up system.

With reliability, unused desert, no pollution, and no fuel costs, the obstacles for large deployment for CSP are cost, aesthetics, land use and similar factors for the necessary connecting high tension lines. Although only a small percentage of the desert is necessary to meet global electricity demand, still a large area must be covered with mirrors or lenses to obtain a significant amount of energy. An important way to decrease cost is the use of a simple design.

### 4.4.1 System designs

During the day the sun has different positions. For low concentration systems (and low temperatures) tracking can be avoided (or limited to a few positions per year) if non-imaging optics are used. For higher concentrations, however, if the mirrors or lenses do not move, then the focus of the mirrors or lenses changes (but also in these cases non-imaging optics provides the widest acceptance angles for a given concentration). Therefore it seems unavoidable that there needs to be a tracking system that follows the position of the sun (for solar photovoltaic a solar tracker is only optional). The tracking system increases the cost and complexity. With this in mind, different designs can be distinguished in how they concentrate the light and track the position of the sun.

## *Parabolic trough designs*

Parabolic trough power plants use a curved, mirrored trough which reflects the direct solar radiation onto a glass tube containing a fluid (also called a receiver, absorber or collector) running the length of the trough, positioned at the focal point of the reflectors. The trough is parabolic along one axis and linear in the orthogonal axis. For change of the daily position of the sun perpendicular to the receiver, the trough tilts east to west so that the direct radiation remains focused on the receiver. However, seasonal changes in the in angle of sunlight parallel to the trough does not require adjustment of the mirrors, since the light is simply concentrated elsewhere on the receiver. Thus the trough design does not require tracking on a second axis (Fig. 4.1).

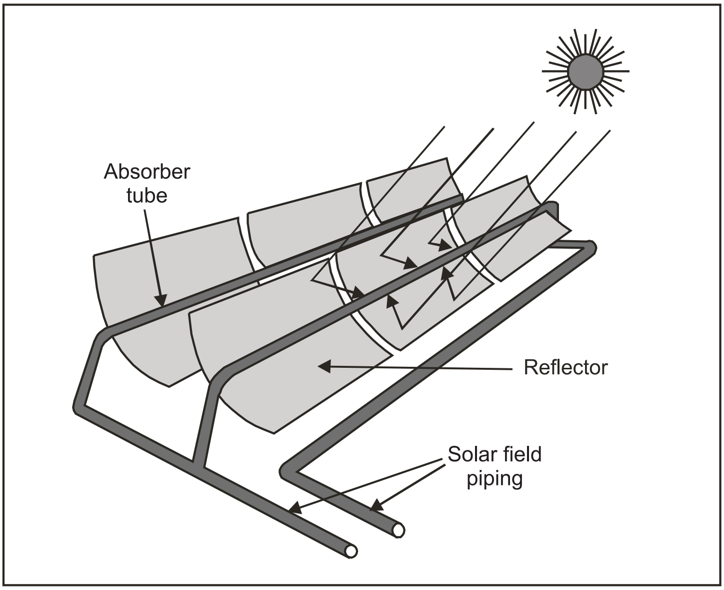



**Figure 4.1** A parabolic trough design. A change in position of the sun parallel to the receiver does not require adjustment of the mirrors.

The receiver may be enclosed in a glass vacuum chamber. The vacuum significantly reduces convective heat loss. A fluid (also called heat transfer fluid) passes through the receiver and becomes very hot. Common fluids are synthetic oil, molten salt and pressurised steam. The fluid containing the heat is transported to a heat engine where about a third of the heat is converted to electricity.

Andasol 1 in Gaudix, Spain, uses the Parabolic Trough design which consists of long parallel rows of modular solar collectors. Tracking the sun from East to West by rotation on one axis, the high precision reflector panels concentrate the solar radiation coming directly from the sun onto an absorber pipe located along the focal line of the collector. A heat transfer medium, such as synthetic oil in car engines, is circulated through the absorber pipes at temperatures up to 400°C and generates live steam to drive the steam turbine generator of a conventional power block.

Full-scale parabolic trough systems consist of many such troughs laid out in parallel over a large area of land. Since 1985 a solar thermal system using this principle has been in full operation in California in the United States. It is called the SEGS system. Other CSP designs lack this kind of long experience and therefore it can currently be said that the parabolic trough design is the most thoroughly proven CSP technology. The solar energy generating system (SEGS) is a collection of nine plants with a total capacity of 350 MW. It is currently the largest operational solar system (both thermal and non-thermal). A newer plant is Nevada Solar One plant with a capacity of 64 MW. Under construction are Andasol 1 and Andasol 2 in Spain with each site having a capacity of 50 MW.

Note however, that those plants have heat storage which requires a larger field of solar collectors relative to the size of the steam turbine-generator to store heat and send heat to the steam turbine at the same time. Heat storage enables better utilisation of the steam turbine. With day and some night time operation of the steam-turbine Andasol 1 at 50 MW peak capacity produces more energy than Nevada Solar One at 64 MW peak capacity, due to the former plant's thermal energy storage system and larger solar field.

553 MW new capacity is proposed in Mojave Solar Park, California. Furthermore, 59 MW hybrid plant with heat storage is proposed near Barstow, California. Near Kuraymat in Egypt, some 40 MW steam is used as input for a gas powered plant. Finally, 25 MW steam input is used for a gas power plant in Hassi R'mel, Algeria.

## *Power tower designs*

Power towers (also known as 'central tower' power plants or 'heliostat' power plants) capture and focus the sun's thermal energy with thousands of tracking mirrors (called heliostats) in roughly a two square mile field. A tower resides in the centre of the heliostat field. The heliostats focus concentrated sunlight on a receiver which sits on top of the tower. Within the receiver the concentrated sunlight heats molten salt to over 1000°F (538°C). The heated molten salt then flows into a thermal storage tank where it is stored, maintaining 98 per cent thermal efficiency, and eventually pumped to a steam generator. The steam drives a standard turbine to generate electricity. This process, also known as the ‘Rankine cycle’ is similar to a standard coal-fired power plant, except it is fuelled by clean and free solar energy.

The advantage of this design above the parabolic trough design is the higher temperature. Thermal energy at higher temperatures can be converted to electricity more efficiently and can be more cheaply stored for later use. Furthermore, there is less need to flatten the ground area. In principle a power tower can be built on a hillside. Mirrors can be flat and plumbing is concentrated in the tower. The disadvantage is that each mirror must have its own dual-axis control, while in the parabolic trough design one axis can be shared for a large array of mirrors. In June 2008, eSolar, a California-based company founded by Idealab CEO Bill Gross with funding from Google, announced a power purchase agreement (PPA) with the utility Southern California Edison to produce 245 megawatts of power. Also, in February 2009, eSolar announced it had licensed its technology to two development partners, the Princeton, N.J.-based NRG Energy, Inc., and the India-based ACME Group. In the deal with NRG, the companies announced plans to jointly build 500 MW of concentrating solar thermal plants throughout the United States. The target goal for the ACME Group was nearly double; ACME plans to start construction on its first eSolar power plant in the year 2012, and will build a total of 1 gigawatt over the next 10 years.

eSolar’s proprietary sun-tracking software coordinates the movement of 24,000 1 $m^2$ mirrors per 1 tower using optical sensors to adjust and calibrate the mirrors in real time. This allows for a high density of reflective material which enables the development of modular CSP power plants in 46 megawatt (MW) units on approximately $\pi$ square mile parcels of land, resulting in a land-to-power ratio of 4 acres (16,000 $m^2$) per 1 MW.

Bright Source Energy entered into a series of power purchase agreements with Pacific Gas and Electric Company in March 2008 for up to 900 MW of electricity, the largest solar power commitment ever made by a utility. Bright Source is currently developing a number of solar power plants in Southern California, with construction of the first plant planned to start in 2009.

In June 2008, Bright Source Energy dedicated its 4–6 MW Solar Energy Development Center (SEDC) in Israel’s Negev Desert. The site, located in the Rotem Industrial Park, features more than 1600 heliostats that track the sun and reflect light onto a 60-m high tower. The concentrated energy is then used to heat a boiler atop the tower to 550 degrees Celsius, generating superheated steam. A working tower power plant is PS10 in Spain with a capacity of 11 MW. The 15 MW Solar Tres plant with heat storage is under construction in Spain. In South Africa, a 100 MW solar power plant is planned with 4000–5000 heliostat mirrors, each having an area of 140 $m^2$.

Morocco is building five solar thermal power plants around Ouasarzate. The sites will produce about 2000 MW by 2012. Over ten thousand hectors of land will be needed to sustain all of the sites.

Out of commission are the 10 MW Solar One (later redeveloped and made into Solar Two) and the 2 MW Themis plants.

A cost/performance comparison between power tower and parabolic trough concentrators was made by the NREL which estimated that by 2020 electricity could be produced from power towers for 5.47 ë/kWh and for 6.21 ë/kWh from parabolic troughs. The capacity factor for power towers was estimated to be 72.9 per cent and 56.2 per cent for parabolic troughs. There is some hope that the development of cheap, durable, mass producible heliostat power plant components could bring this cost down.

## *Dish designs*

A dish stirling system uses a large, reflective, parabolic dish (similar in shape to satellite television dish). It focuses all the sunlight that strikes the dish up onto to a single point above the dish, where a receiver captures the heat and transforms it into a useful form. Typically the dish is coupled with a stirling engine in a Dish-Stirling System, but also sometimes a steam engine is used. These create rotational kinetic energy that can be converted to electricity using an electric generator.

The advantage of a dish system is that it can achieve much higher temperatures due to the higher concentration of light (as in tower designs). Higher temperatures lead to better conversion to electricity and the dish system is very efficient on this point. However, there are also some disadvantages. Heat to electricity conversion requires moving parts and that result in maintenance. In general, a centralised approach for this conversion is better than the decentralised concept in the dish design. Second, the (heavy) engine is part of the moving structure, which requires a rigid frame and strong tracking system. Furthermore, parabolic mirrors are used instead of flat mirrors and tracking must be dual-axis.

In 2005 Southern California Edison announced an agreement to purchase solar powered Stirling engines from Stirling Energy Systems over a 20 year period and in quantities (20,000 units) sufficient to generate 500 MW of electricity. Stirling Energy Systems announced another agreement with San Diego Gas and Electric to provide between 300 and 900 megawatts of electricity. In January 2010, Stirling Energy Systems and Tessera Solar commissioned the first demonstration 1.5 MW power plant (Maricopa solar) using Stirling technology in Peoria, Arizona. In July 2011, Iran inaugurated Iran's biggest solar power plant in Mashhad which produce 72,000 kW/h electricity per year.

### *Fresnel reflectors*

A linear Fresnel reflector power plant uses a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light onto one or more linear receivers positioned above the mirrors. On top of the receiver, a small parabolic mirror can be attached for further focusing the light. These systems aim to offer lower overall costs by sharing a receiver between several mirrors (as compared with trough and dish concepts), while still using the simple line-focus geometry with one axis for tracking. This is similar to the trough design (and different from central towers and dishes with dual-axis). The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). The mirrors also do not need to support the receiver, so they are structurally simpler. When suitable aiming strategies are used (mirrors aimed at different receivers at different times of day), this can allow a denser packing of mirrors on available land area.

Recent prototypes of these types of systems have been built in Australia (CLFR) and by Solarmundo in Belgium. The Solarmundo research and development project, with its pilot plant at Liège, was closed down after successful proof of concept of the Linear Fresnel technology. Subsequently, Solar Power Group GmbH (SPG), based in Munich, Germany, was founded by some Solarmundo team members. A Fresnel-based prototype with direct steam generation was built by SPG in conjunction with the German Aerospace Center (DLR).

In May 2008, the German Solar Power Group GmbH and the Spanish Laer S.L. agreed the joint execution of a solar thermal power plant in central Spain. This will be the first commercial solar thermal power plant in Spain based on the Fresnel collector technology of the Solar Power Group. The planned size of the power plant will be 10 MW a solar thermal collector field with a fossil co-firing unit as backup system.

The start of constructions is planned for 2012. The project is located in Gotarrendura, a small renewable energy pioneering village, about 100 km northwest of Madrid, Spain.

A Multi-Tower Solar Array (MTSA) concept, that uses a point-focus Fresnel reflector idea, has also been developed, but has not yet been prototyped. Since March 2009, the Fresnel solar power plant PE 1 of the German company Novatec Biosol is in commercial operation in southern Spain. The solar thermal power plant is based on linear Fresnel collector technology and has an electrical capacity of 1.4 MW. Beside a conventional power block, PE 1 comprises a solar boiler with mirror surface of around 18,000 m$^2$. The steam is generated by concentrating direct solar irradiation onto a linear receiver which is 7.40 m above the ground. An absorber tube is positioned in the focal line of the mirror field in which water is evaporated directly into saturated steam at 270°C and at a pressure of 55 bar by the concentrated solar energy.

## *Linear Fresnel reflector technologies*

Rival single axis tracking technologies include the relatively new linear Fresnel reflector (LFR) and compact-LFR (CLFR) technologies. The LFR differs from that of the parabolic trough in that the absorber is fixed in space above the mirror field. Also, the reflector is composed of many low row segments, which focus collectively on an elevated long tower receiver running parallel to the reflector rotational axis.

This system offers a lower cost solution as the absorber row is shared among several rows of mirrors. However, one fundamental difficulty with the LFR technology is the avoidance of shading of incoming solar radiation and blocking of reflected solar radiation by adjacent reflectors. Blocking and shading can be reduced by using absorber towers elevated higher or by increasing the absorber size, which allows increased spacing between reflectors remote from the absorber. Both these solutions increase costs, as larger ground usage is required.

The CLFR offers an alternate solution to the LFR problem. The classic LFR has only one linear absorber on a single linear tower. This prohibits any option of the direction of orientation of a given reflector. Since this technology would be introduced in a large field, one can assume that there will be many linear absorbers in the system. Therefore, if the linear absorbers are close enough, individual reflectors will have the option of directing reflected solar radiation to at least two absorbers. This additional factor gives potential for more densely packed arrays, since patterns of alternative reflector inclination can be set up such that closely packed reflectors can be positioned without shading and blocking.

CLFR power plants offer reduced costs in all elements of the solar array. These reduced costs encourage the advancement of this technology. Features that enhance the cost effectiveness of this system compared to that of the parabolic trough technology include minimised structural costs, minimised parasitic pumping losses, and low maintenance. Minimised structural costs are attributed to the use of flat or elastically curved glass reflectors instead of costly sagged glass reflectors are mounted close to the ground. Also, the heat transfer loop is separated from the reflector field, avoiding the cost of flexible high pressure lines required in trough systems. Minimised parasitic pumping losses are due to the use of water for the heat transfer fluid with passive direct boiling. The use of glass-evacuated tubes ensures low-radiative losses and is inexpensive. Studies of existing CLFR plants have been shown to deliver tracked beam to electricity efficiency of 19 per cent on an annual basis as a preheater.

### *Fresnel lenses*

Prototypes of Fresnel lens concentrators have been produced for the collection of thermal energy by International Automated Systems. No full-scale thermal systems using Fresnel lenses are known to be in operation, although products incorporating Fresnel lenses in conjunction with photovoltaic cells are already available. The advantage of this design is that lenses are cheaper than mirrors. Furthermore, if a material is chosen that has some flexibility, then a less rigid frame is required to withstand wind load. A new concept of a lightweight, 'non-disruptive' solar concentrator technology using asymmetric Fresnel lenses that occupies minimal ground surface area and allows for large amounts of concentrated solar energy per concentrator is seen in the 'Desert Blooms' project, though a prototype has yet to be made.

### *MicroCSP*

'MicroCSP' references solar thermal technologies in which concentrating solar power (CSP) collectors are based on the designs used in traditional Concentrating Solar Power systems found in the Mojave Desert but are smaller in collector size, lighter and operate at lower thermal temperatures usually below 315°C (600°F). These systems are designed for modular field or rooftop installation where they are easy to protect from high winds, snow and humid deployments. Solar manufacturer Sopogy completed construction on a 1 MW CSP plant at the Natural Energy Laboratory of Hawaii. MicroCSP is used for community-sized power plants (1 MW to 50 MW), for industrial, agricultural and manufacturing 'process heat' applications, and when large amounts of hot water are needed, such as resort swimming pools, water parks, large laundry facilities, sterilisation, distillation and other such uses.

## 4.4.2 Heat exchange

Heat in a solar thermal system is guided by five basic principles: heat gain, heat transfer, heat storage, heat transport, and heat insulation. Here, heat is the measure of the amount of thermal energy an object contains and is determined by the temperature, mass and specific heat of the object. Solar thermal power plants use heat exchangers that are designed for constant working conditions, to provide heat exchange.

Heat gain is the heat accumulated from the sun in the system. Solar thermal heat is trapped using the greenhouse effect; the greenhouse effect in this case is the ability of a reflective surface to transmit short wave radiation and reflect long wave radiation. Heat and infrared radiation (IR) are produced when short wave radiation light hits the absorber plate, which is then trapped inside the collector. Fluid, usually water, in the absorber tubes collect the trapped heat and transfer it to a heat storage vault.

Heat is transferred either by conduction or convection. When water is heated, kinetic energy is transferred by conduction to water molecules throughout the medium. These molecules spread their thermal energy by conduction and occupy more space than the cold slow moving molecules above them. The distribution of energy from the rising hot water to the sinking cold water contributes to the convection process. Heat is transferred from the absorber plates of the collector in the fluid by conduction. The collector fluid is circulated through the carrier pipes to the heat transfer vault. Inside the vault, heat is transferred throughout the medium through convection. Heat storage enables solar thermal plants to produce electricity during hours without sunlight. Heat is transferred to a thermal storage medium in an insulated reservoir during hours with sunlight, and is withdrawn for power generation during hours lacking sunlight. Thermal storage mediums will be discussed in a heat storage section. Rate of heat transfer is related to the conductive and convection medium as well as the temperature differences. Bodies with large temperature differences transfer heat faster than bodies with lower temperature differences. Heat transport refers to the activity in which heat from a solar collector is transported to the heat storage vault. Heat insulation is vital in both heat transport tubing as well as the storage vault. It prevents heat loss, which in turn relates to energy loss or decrease in the efficiency of the system.

### 4.4.3 Heat storage

Heat storage allows a solar thermal plant to produce electricity at night and on overcast days. This allows the use of solar power for base-load generation as well as peak power generation, with the potential of displacing both coal and natural gas fired power plants. Additionally, the utilisation of the generator is higher which reduces cost. Heat is transferred to a thermal storage medium in an insulated reservoir during the day, and withdrawn for power generation at night. Thermal storage media include pressurised steam, concrete, a variety of phase change materials, and molten salts such as sodium and potassium nitrate.

#### *Steam accumulator*

The PS10 solar power tower stores heat in tanks as pressurised steam at 50 bar and 285°C. The steam condenses and flashes back to steam, when pressure is lowered. Storage is for one hour. It is suggested that longer storage is possible, but that has not been proven yet in an existing power plant.

## *Molten salt storage*

A variety of fluids have been tested to transport the sun's heat, including water, air, oil, and sodium, but molten salt was selected as best. Molten salt is used in solar power tower systems because it is liquid at atmosphere pressure, it provides an efficient, low-cost medium in which to store thermal energy, its operating temperatures are compatible with today's high-pressure and high-temperature steam turbines, and it is non-flammable and nontoxic. In addition, molten salt is used in the chemical and metals industries as a heat-transport fluid, so experience with molten-salt systems exists in non-solar settings.

The molten salt is a mixture of 60 per cent sodium nitrate and 40 per cent potassium nitrate, commonly called saltpetre. New studies show that calcium nitrate could be included in the salts mixture to reduce costs and with technical benefits. The salt melts at 220°C (430°F) and is kept liquid at 290°C (550°F) in an insulated storage tank. The uniqueness of this solar system is in de-coupling the collection of solar energy from producing power, electricity can be generated in periods of inclement weather or even at night using the stored thermal energy in the hot salt tank. Normally tanks are well insulated and can store thermal energy for up to a week. As an example of their size, tanks that provide enough thermal storage to power a 100-megawatt turbine for four hours would be about 9 m (30 ft) tall and 24 m (80 ft) in diameter. The Andasol power plant in Spain is the first commercial solar thermal power plant to utilise molten salt for heat storage and night-time generation. It came online March 2009. On July 4, 2011, a company in Spain celebrated an historic moment for the solar industry: Torresol's 19.9 MW concentrating solar power plant became the first ever to generate uninterrupted electricity for 24 hours straight. It achieved this using a molten salt heat storage design.

## *Graphite heat storage*

Direct: The proposed power plant in Cloncurry Australia will store heat in purified graphite. The plant has a power tower design. The graphite is located on top of the tower. Heat from the heliostats goes directly to the storage. Heat for energy production is drawn from the graphite. This simplifies the design.

*Indirect:* Molten salt coolants are used to transfer heat from the reflectors to heat storage vaults. The heat from the salts is transferred to a secondary heat transfer fluid via a heat exchanger and then to the storage media or alternatively, the salts can be used to directly heat graphite. Graphite is used as it has relatively low costs and compatibility with liquid fluoride salts. The high mass and volumetric heat capacity of graphite provide an efficient storage medium.

### *Phase-change materials for storage*

Phase-change material (PCMs) offers an alternate solution in energy storage. Using a similar heat transfer infrastructure, PCMs have the potential of providing a more efficient means of storage. PCMs can be either organic or inorganic materials. Advantages of organic PCMs include no corrosives, low or no undercooling, and chemical and thermal stability. Disadvantages include low phase-change enthalpy, low thermal conductivity, and flammability. Inorganics are advantageous with greater phase-change enthalpy, but exhibit disadvantages with undercooling, corrosion, phase separation, and lack of thermal stability. The greater phase-change enthalpy in inorganic PCMs make hydrate salts a strong candidate in the solar energy storage field.

### 4.4.4 Use of water

A design which requires water for condensation or cooling may conflict with location of solar thermal plants in desert areas with good solar radiation but limited water resources. The conflict is illustrated by plans of Solar Millennium, a German company, to build a plant in the Amargosa Valley of Nevada which would require 20 per cent of the water available in the area. Some other projected plants by the same and other companies in the Mojave Desert of California may also be affected by difficulty in obtaining adequate and appropriate water rights. California water law currently prohibits use of potable water for cooling.

Other designs require less water. The proposed Ivanpah Solar Power Facility in south-eastern California will conserve scarce desert water by using air-cooling to convert the steam back into water. Compared to conventional wet-cooling, this results in a 90 per cent reduction in water usage at the cost of some loss of efficiency. The water is then returned to the boiler in a closed process which is environmentally friendly.

## 4.5 Conversion rates from solar energy to electrical energy

Of all of these technologies, the solar dish/stirling engine has the highest energy efficiency. A single solar dish-Stirling engine installed at Sandia National Laboratories National Solar Thermal Test Facility produces as much as 25 kW of electricity, with a conversion efficiency of 31.25 per cent. Solar parabolic trough plants have been built with efficiencies of about 20 per cent. Fresnel reflectors have an efficiency that is slightly lower (but this is compensated by the denser packing).

The gross conversion efficiencies (taking into account that the solar dishes or troughs occupy only a fraction of the total area of the power plant) are determined by net generating capacity over the solar energy that falls on the total area of the solar plant. The 500-MW SCE/SES plant would extract about 2.75 per cent of the radiation (1 kW/m$^2$) that falls on its 4500 acres (18.2 km$^2$). For the 50 MW AndaSol Power Plant that is being built in Spain (total area of 1300 × 1500 m = 1.95 km$^2$) gross conversion efficiency comes out at 2.6 per cent.

Furthermore, efficiency does not directly relate to cost: On calculating total cost, both efficiency and the cost of construction and maintenance should be taken into account.

### 4.5.1 Levelised cost

Since a solar power plant does not use any fuel, the cost consists mostly of capital cost with minor operational and maintenance cost. If the lifetime of the plant and the interest rate is known, then the cost per kWh can be calculated. This is called the levelised energy cost.

The first step in the calculation is to determine the investment for the production of 1 kWh in a year. Example, the fact sheet of the Andasol 1 project shows a total investment of 310 million Euros for a production of 179 GWh a year. Since 179 GWh is 179 million kWh, the investment per kWh a year production is 310/179 = 1.73 euro. Another example is Cloncurry solar power station in Australia. It is planned to produce 30 million kWh a year for an investment of 31 million Australian dollars. So, if this is achieved in reality, the cost would be 1.03 Australian dollar for the production of 1 kWh in a year. This would be significantly cheaper than Andasol 1, which can partially be explained by the higher radiation in Cloncurry over Spain. The investment per kWh cost for one year should not be confused with the cost per kWh over the complete lifetime of such a plant.

In most cases the capacity is specified for a power plant (for instance Andasol 1 has a capacity of 50 MW). This number is not suitable for comparison, because the capacity factor can differ. If a solar power plant has heat storage, then it can also produce output after sunset, but that will not change the capacity factor, it simply displaces the output. The average capacity factor for a solar power plant, which is a function of tracking, shading and location, is about 20 per cent, meaning that a 50 MW capacity power plant will typically provide a yearly output of 50 MW × 24 hours × 365 days × 20 per cent = 87,600 MWh/year or 87.6 GWh/year.

Although the investment for 1 kWh year production is suitable for comparing the price of different solar power plants, it does not give the price per kWh yet. The way of financing has a great influence on the final price. If the technology is proven, an interest rate of 7 per cent should be possible. However, for a new technology investors want a much higher rate to compensate for the higher risk. This has a significant negative effect on the price per kWh. Independent of the way of financing, there is always a linear relation between the investment per kWh production in a year and the price for 1 kWh (before adding operational and maintenance cost). In other words, if by enhancements of the technology the investments drop by 20 per cent, then the price per kWh also drops by 20 per cent.

If a way of financing is assumed where the money is borrowed and repaid every year, in such way that the debt and interest decreases. For a lifetime of 25 years and an interest rate of 7 per cent, the division factor is 11.65. For example, the investment of Andasol 1 was 1.73 euro per kWh, divided by 11.65 results in a price of 0.15 euro per kWh. If 1 per cent operation and maintenance cost is added, then the levelised cost is 0.16 euro per kWh. Other ways of financing, different way of debt repayment, different lifetime expectation, different interest rate, may lead to a significantly different number.

If the cost per kWh may follow the inflation, then the inflation rate can be added to the interest rate. If an investor puts his money on the bank for 7 per cent, then he is not compensated for inflation. However, if the cost per kWh is raised with inflation, then he is compensated and he can add 2 per cent (a normal inflation rate) to his return. The Andasol 1 plant has a guaranteed feed-in tariff of 0.21 euro for 25 years. If this number is fixed, after 25 years with 2 per cent inflation, 0.21 euro will have a value comparable with 0.13 euro now. Finally, there is some gap between the first investment and the first production of electricity. This increases the investment with the interest over the period that the plant is not active yet. The modular solar dish (but also solar photovoltaic and wind power) have the advantage that electricity production starts after first construction. Given the fact that solar thermal power is reliable, can deliver peak load and does not cause pollution, a price of US$0.10 per kWh starts to become competitive. Although a price of US$0.06 has been claimed with some operational cost a simple target is 1 dollar (or lower) investment for 1 kWh production in a year.

## 4.6 Solar pond

A solar pond is a pool of saltwater which acts as a large-scale solar thermal energy collector with integral heat storage for supplying thermal energy. A solar pond can be used for various applications, such as process heating, desalination, refrigeration, drying and solar power generation.

A solar pond is simply a pool of saltwater which collects and stores solar thermal energy. The saltwater naturally forms a vertical salinity gradient also known as a 'halocline', in which low-salinity water floats on top of high-salinity water. The layers of salt solutions increase in concentration (and therefore density) with depth. Below a certain depth, the solution has a uniformly high salt concentration.

There are three distinct layers of water in the pond:

1. The top layer, which has a low salt content
2. An intermediate insulating layer with a salt gradient, which establishes a density gradient that prevents heat exchange by natural convection
3. The bottom layer, which has a high salt content

If the water is relatively translucent, and the pond's bottom has high optical absorption, then nearly all of the incident solar radiation (sunlight) will go into heating the bottom layer.

When solar energy is absorbed in the water, its temperature increases, causing thermal expansion and reduced density. If the water were fresh, the low-density warm water would float to the surface, causing a convection current. The temperature gradient alone causes a density gradient that decreases with depth. However the salinity gradient forms a density gradient that increases with depth, and this counteracts the temperature gradient, thus preventing heat in the lower layers from moving upwards by convection and leaving the pond. This means that the temperature at the bottom of the pond will rise to over 90°C while the temperature at the top of the pond is usually around 30°C. A natural example of these effects in a saline water body is Solar Lake in the Sinai Peninsula of Egypt.

The heat trapped in the salty bottom layer can be used for many different purposes, such as the heating of buildings or industrial hot water or to drive an organic Rankine cycle turbine or Stirling engine for generating electricity.

Advantages and disadvantages

1. The approach is particularly attractive for rural areas in developing countries. Very large area collectors can be set up for just the cost of the clay or plastic pond liner.
2. The evaporated surface water needs to be constantly replenished.
3. The accumulating salt crystals have to be removed and can be both a valuable by-product and a maintenance expense.
4. No need of a separate collector for this thermal storage system.

### 4.6.1 Efficiency

The energy obtained is in the form of low-grade heat of 70–80°C compared to an assumed 20°C ambient temperature. According to the second law of thermodynamics (Carnot-cycle), the maximum theoretical efficiency of a solar concentrator system with molten salt is: 1 − (273 + 20) / (273 + 80) = 17 per cent. By comparison, a power plant's heat engine delivering high-grade heat at 800°C would have a maximum theoretical limit of 73 per cent for converting heat into useful work (and thus would be forced to divest as little as 27 per cent in waste heat to the cold temperature reservoir at 20°C). The low efficiency of solar ponds is usually justified with the argument that the 'collector', being just a plastic-lined pond, might potentially result in a large-scale system that is of lower overall levelised energy cost than a solar concentrating system.

*Examples:* The largest operating solar pond for electricity generation was the Beit HaArava pond built in Israel and operated up until 1988. It had an area of 2,10,000 $m^2$ and gave an electrical output of 5 MW.

The first solar pond in India (6000 sq. metres) was built at Bhuj. The project was sanctioned under the National Solar Pond Program by the Ministry of Non-conventional Energy Sources in 1987 and completed in 1993 after a sustained collaborative effort by TERI, the Gujarat Energy Development Agency, and the GDDC. The solar pond successfully demonstrated the expediency of the technology by supplying 80,000 litres of hot water daily to the plant. The Energy and Resources Institute provided all technical inputs and took up the complete execution of research, development, and demonstration. TERI operated and maintained this facility until 1996 before handing it over to the GDDC. The solar pond functioned effortlessly till the year 2000 when severe financial losses crippled GDDC. Subsequently, the Bhuj earthquake left the Kutch Dairy non-functional.

The 0.8-acre (3,200 $m^2$) solar pond powering 20 per cent of Bruce Foods Corporation's operations El Paso, Texas is the second largest in the US. It is also the first ever salt-gradient solar pond in the US.

## 4.7 Solar water heating

Solar water heating or solar hot water is water heated by the use of solar energy. Solar water heating systems are generally composed of solar thermal collectors, a water storage tank or another point of usage, interconnecting pipes and a fluid system to move the heat from the collector to the tank. This thermodynamic approach is distinct from semiconductor photovoltaic (PV) cells that generate electricity from light; solar water heating deals with the direct heating of liquids by the sun where no electricity is directly generated. A solar water heating system may use electricity for pumping the fluid, and have a reservoir or tank for heat storage and subsequent use. The water can be heated for a wide variety of uses, including home, business and industrial uses. Heating swimming pools, underfloor heating or energy input for space heating or cooling are common examples of solar water heating.

A solar water heating system can form part of a solar thermal cooling system, promoting efficient temperature control of buildings or parts thereof. During cool conditions, the same system can provide hot water. Solar heating of buildings in temperate climates has a season-problem: In winter, when most heating is needed, least is available from the sun. This can often be solved by storing solar heat in the ground or in groundwater (Seasonal thermal store). Hot water heated by the sun is used in many ways. While perhaps best known in a residential setting to provide domestic hot water, solar hot water also has industrial applications, e.g. to generate electricity. Designs suitable for hot climates can be much simpler and cheaper, and can be considered an appropriate technology for these places. The global solar thermal market is dominated by China, Europe, Japan and India.

In order to heat water using solar energy, a collector, often fastened to a roof or a wall facing the sun, heats working fluid that is either pumped (active system) or driven by natural convection (passive system) through it. The collector could be made of a simple glass topped insulated box with a flat solar absorber made of sheet metal attached to copper pipes and painted black or a set of metal tubes surrounded by an evacuated (near vacuum) glass cylinder. In industrial cases a parabolic mirror can concentrate sunlight on the tube. Heat is stored in a hot water storage tank.

The volume of this tank needs to be larger with solar heating systems in order to allow for bad weather, and because the optimum final temperature for the solar collector is lower than a typical immersion or combustion heater. The heat transfer fluid (HTF) for the absorber may be the hot water from the tank, but more commonly (at least in active systems) is a separate loop of fluid containing anti-freeze and a corrosion inhibitor which delivers heat to the tank through a heat exchanger (commonly a coil of copper tubing within the tank). Another lower-maintenance concept is the ‘drain-back’: no anti-freeze is required; instead all the piping is sloped to cause water to drain back to the tank. The tank is not pressurised and is open to atmospheric pressure. As soon as the pump shuts off, flow reverses and the pipes are empty before freezing could occur.

Residential solar thermal installations fall into two groups: passive (sometimes called compact) and active (sometimes called pumped) systems. Both typically include an auxiliary energy source (electric heating element or connection to a gas or fuel oil central heating system) that is activated when the water in the tank falls below a minimum temperature setting such as 55°C. Hence, hot water is always available. The combination of solar water heating and using the back-up heat from a wood stove chimney to heat water can enable a hot water system to work all year round in cooler climates, without the supplemental heat requirement of a solar water heating system being met with fossil fuels or electricity.

When a solar water heating and hot-water central heating system are used in conjunction, solar heat will either be concentrated in a pre-heating tank that feeds into the tank heated by the central heating or the solar heat exchanger will replace the lower heating element and the upper element will remain in place to provide for any heating that solar cannot provide. However, the primary need for central heating is at night and in winter when solar gain is lower. Therefore, solar water heating for washing and bathing is often a better application than central heating because supply and demand are better matched. In many climates, a solar hot water system can provide up to 85 per cent of domestic hot water energy. This can include domestic non-electric concentrating solar thermal systems. In many northern European countries, combined hot water and space heating systems (solar combisystems) are used to provide 15–25 per cent of home heating energy.

### 4.7.1 System design requirements

The type, complexity and size of a solar water heating system are mostly determined by:

1. The temperature and amount of the water required from the system
2. The changes in ambient temperature and solar radiation between summer and winter
3. The changes in ambient temperature during the day–night cycle
4. The possibility of the potable water or collector fluid overheating
5. The possibility of the potable water or collector fluid freezing

The minimum requirements of the system are typically determined by the amount or temperature of hot water required during winter, when a system's output and incoming water temperature are typically at their lowest. The maximum output of the system is determined by the need to prevent the water in the system from becoming too hot or, in the systems that overheating is avoided, the desire to waste money on unneeded components.

### 4.7.2 Freeze protection

Freeze protection measures prevent damage to the system due to the expansion of freezing transfer fluid. Drainback systems drain the transfer fluid from the system when the pump stops. Many indirect systems use antifreeze (e.g. propylene glycol) in the heat transfer fluid.

In some direct systems, the collectors can be manually drained when freezing is expected. This approach is common in climates where freezing temperatures do not occur often, but is somewhat unreliable since the operator can forget to drain the system. Other direct systems use freeze-tolerant collectors made with flexible polymers such as silicone rubber.

### 4.7.3 Overheat protection

When no hot water has been used for a day or two, the fluid in the collectors and storage can reach very high temperatures in all systems except for those of the drain-back variety. When the storage tank in a drain-back system reaches its desired temperature, the pumps are shut off, putting an end to the heating process and thus preventing the storage tank from overheating. One method of providing over heat protection is to dump the heat into a hot tub. Some active systems deliberately cool the water in the storage tank by circulating hot water through the collector at times when there is little sunlight or at night, causing increased heat loss. This is particularly ineffective in systems that use evacuated tube collectors, due to their superior insulation. No matter the collector type, however, they can still overheat and ultimately rely on the operation of temperature and pressure relief valves.

### 4.7.4 Types of solar water heating systems

Solar water heaters can be either active or passive. An active system uses an electric pump to circulate the heat-transfer fluid; a passive system has no pump. The amount of hot water a solar water heater produces depends on the type and size of the system, the amount of sun available at the site, proper installation, and the tilt angle and orientation of the collectors.

Solar water heaters are also characterised as open loop (also called direct) or closed loop (also called indirect). An open-loop system circulates household (potable) water through the collector. A closed-loop system uses a heat-transfer fluid (water or diluted antifreeze, for example) to collect heat and a heat exchanger to transfer the heat to household water.

#### *Direct and indirect systems*

Direct or open-loop systems circulate potable water through the collectors. They are cheaper than indirect systems and offer superior heat transfer from the collectors to the storage tank, but have many drawbacks:

1. They offer little or no overheat protection.
2. They offer little or no freeze protection.
3. The collectors will accumulate scale in hard water areas.

They are often not considered suitable for cold climates since, in the event of the collector being damaged by a freeze, pressurised water lines will force water to gush from the freeze-damaged collector until the problem is noticed and rectified (Fig. 4.2). Indirect or closed loop systems use a heat exchanger that separates the potable water from the fluid, known as the 'heat-transfer fluid' (HTF), which circulates through the collector. The two most common HTFs are water and an antifreeze/water mix that typically uses non-toxic propylene glycol. After being heated in the panels, the HTF travels to the heat exchanger, where its heat is transferred to the potable water. Though slightly more expensive, indirect systems offer freeze protection and typically offer overheat protection as well.

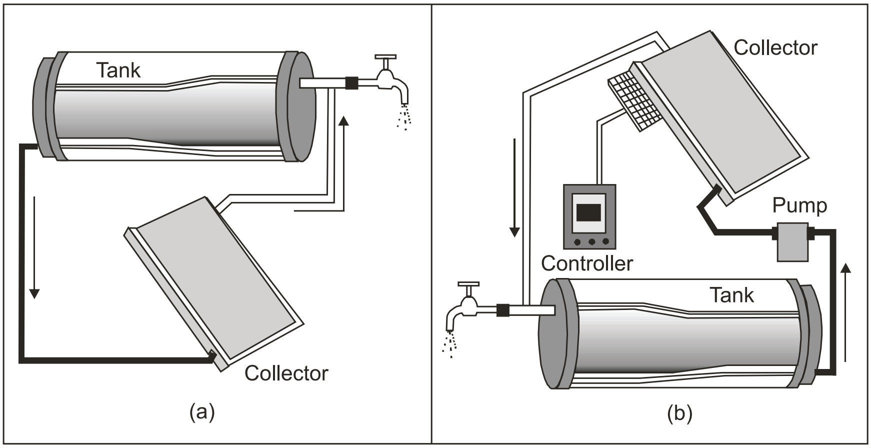



**Figure 4.2** Direct systems: (a) passive CHS system with tank above collector, and (b) active system with pump and controller driven by a photovoltaic panel.

## *Passive and active systems*

Passive systems rely on heat-driven convection or heat pipes to circulate water or heating fluid in the system. Passive solar water heating systems cost less and have extremely low or no maintenance, but the efficiency of a passive system is significantly lower than that of an active system, and overheating and freezing are major concerns. Active systems use one or more pumps to circulate water and/or heating fluid in the system (Fig. 4.3).

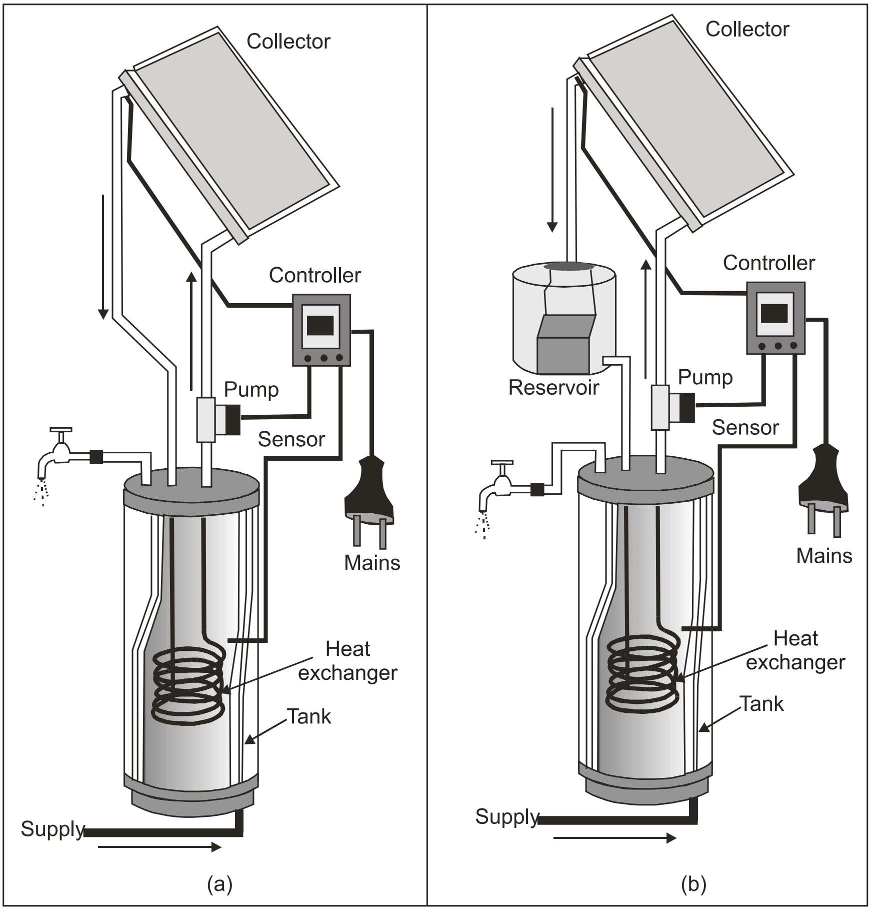



**Figure 4.3** Indirect active systems: (a) indirect system with heat exchanger in tank, (b) drainback system with drainback reservoir. In these schematics the controller and pump are driven by mains electricity.

Though slightly more expensive, active systems offer several advantages:

1. The storage tank can be situated lower than the collectors, allowing increased freedom in system design and allowing pre-existing storage tanks to be used.
2. The storage tank can always be hidden from view.
3. The storage tank can be placed in conditioned or semi-conditioned space, reducing heat loss.
4. Drainback tanks can be used.
5. Superior efficiency
6. Increased control over the system

Modern active solar water systems have electronic controllers that offer a wide-range of functionality, such as the modification of settings that control the system, interaction with a backup electric or gas-driven water heater, calculation and logging of the energy saved by a SWH system, safety functions, remote access, and various informative displays, such as temperature readings.

The most popular pump controller is a differential controller that senses temperature differences between water leaving the solar collector and the water in the storage tank near the heat exchanger. In a typical active system, the controller turns the pump on when the water in the collector is about 8–10°C warmer than the water in the tank, and it turns the pump off when the temperature difference approaches 3–5°C. This ensures the water always gains heat from the collector when the pump operates and prevents the pump from cycling on and off too often. (In direct systems this ‘on differential’ can be reduced to around 4C because there is no heat exchanger impediment.)

Some active SWH systems use energy obtained by a small photovoltaic (PV) panel to power one or more variable-speed DC pump(s). In order to ensure proper performance and longevity of the pump(s), the DC-pump and PV panel must be suitably matched. These systems are almost always of the antifreeze variety and often do not use controllers, as the collectors will almost always be hot when the pump(s) are operating (i.e. when the sun is bright). Sometimes, however, a differential controller (that can also be powered by the DC output of a PV panel) is used to prevent the operation of the pumps when there is sunlight to power the pump but the collectors are still cooler than the water in storage. One advantage of a PV-driven system is that solar hot water can still be collected during a power outage if the sun is shining.

An active solar water heating system can also be equipped with a bubble pump (also known as geyser pump) instead of an electric pump. A bubble pump circulates the heat transfer fluid (HTF) between collector and storage tank using solar power and without any external energy source and is suitable for flat panel as well as vacuum tube systems. In a bubble pump system, the closed HTF circuit is under reduced pressure, which causes the liquid to boil at low temperature as it is heated by the sun. The steam bubbles form a geyser pump, causing an upward flow. The system is designed such that the bubbles are separated from the hot fluid and condensed at the highest point in the circuit, after which the fluid flows downward towards the heat exchanger caused by the difference in fluid levels. The HTF typically arrives at the heat exchanger at 70°C and returns to the circulating pump at 50°C. In frost prone climates the HTF is water with propylene glycol antifreeze added, usually in the ratio of 60 to 40. Pumping typically starts at about 50°C and increases as the sun rises until equilibrium is reached depending on the efficiency of the heat exchanger, the temperature of the water being heated and the strength of the sun.

### *Passive direct systems*

An integrated collector storage (ICS or Batch Heater) system uses a tank that acts as both storage and solar collector. Batch heaters are basically thin rectilinear tanks with a glass side, facing south. They are simple and less costly than plate and tube collectors, but they sometimes require extra bracing if installed on a roof (since they are heavy when filled with water [400–700 lbs],) suffer from significant heat loss at night since the side facing the sun is largely uninsulated, and are only suitable in moderate climates. A convection heat storage unit (CHS) system is similar to an ICS system, except the storage tank and collector are physically separated and transfer between the two is driven by convection. CHS systems typically use standard flat-plate type or evacuated tube collectors, and the storage tank must be located above the collectors for convection to work properly. The main benefit of a CHS systems over an ICS system is that heat loss is largely avoided since: (i) the storage tank can be better insulated, and (ii) since the panels are located below the storage tank, heat loss in the panels will not cause convection, as the cold water will prefer to stay at the lowest part of the system (Fig. 4.4).

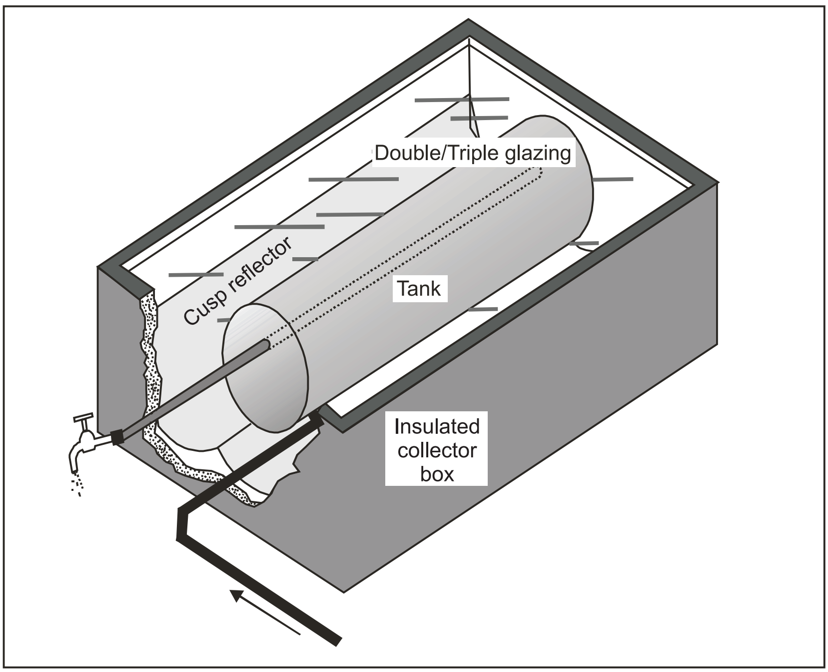



**Figure 4.4** An integrated collector storage (ICS) system

### *Active indirect systems: Drainback and antifreeze*

Pressurised antifreeze or pressurised glycol systems use a mix of antifreeze (almost always non-toxic propylene glycol) and water mix for HTF in order to prevent freeze damage.

Though effective at preventing freeze damage, antifreeze systems have many drawbacks:

1. If the HTF gets too hot (for example, when the homeowner is on vacation), the glycol degrades into acid. After degradation, the glycol not only fails to provide freeze protection, but also begins to eat away at the solar loop's components: The collectors, the pipes, the pump, etc. Due to the acid and excessive heat, the longevity of parts within the solar loop is greatly reduced.
2. Most do not feature drainback tanks, so the system must circulate the HTF—regardless of the temperature of the storage tank—in order to prevent the HTF from degrading. Excessive temperatures in the tank cause increased scale and sediment build-up, possible severe burns if a tempering valve is not installed, and, if a water heater is being used for storage, possible failure of the water heater's thermostat.
3. The glycol/water HTF must be replaced every 3–8 years, depending on the temperatures it has experienced.
4. Some jurisdictions require double-walled heat exchangers even though propylene glycol is non-toxic.
5. Even though the HTF contains glycol to prevent freezing, it will still circulate hot water from the storage tank into the collectors at low temperatures (e.g. below 40 degrees Fahrenheit), causing substantial heat loss.

A drainback system is an indirect active system where the HTF (almost always pure water) circulates through the collector, being driven by a pump. The collector piping is not pressurised and includes an open drainback reservoir that is contained in conditioned or semi-conditioned space. If the pump is switched off, the HTF drains into the drainback reservoir and none remains in the collector. Since the system relies upon being able to drain properly, all piping above the drainback tank, including the collectors, must slope downward in the direction of the drainback tank. Installed properly, the collector cannot be damaged by freezing or overheating. Drainback systems require no maintenance other than the replacement of failed system components.

## 4.7.5 Collectors used in modern domestic SWH systems

Solar thermal collectors capture and retain heat from the sun and transfer this heat to a liquid. Two important physical principles govern the technology of solar thermal collectors:

1. Any hot object ultimately returns to thermal equilibrium with its environment, due to heat loss from the hot object. The processes that result in this heat loss are conduction, convection and radiation. The efficiency of a solar thermal collector is directly related to heat losses from the collector surface (efficiency being defined as the proportion of heat energy that can be retained for a predefined period of time). Within the context of a solar collector, convection and radiation are the most important sources of heat loss. Thermal insulation is used to slow down heat loss from a hot object to its environment. This is actually a direct manifestation of the second law of thermodynamics but we may term this the 'equilibrium effect'.
2. Heat is lost more rapidly if the temperature difference between a hot object and its environment is larger. Heat loss is predominantly governed by the thermal gradient between the temperature of the collector surface and the ambient temperature. Conduction, convection as well as radiation occur more rapidly over large thermal gradients. We may term this the 'delta-t effect'.

The simplest approach to solar heating of water is to simply mount a metal tank filled with water in a sunny place. The heat from the sun would then heat the metal tank and the water inside. Indeed, this was how the very first SWH systems worked more than a century ago. However, this setup would be inefficient due to an oversight of the equilibrium effect, above: as soon as heating of the tank and water begins, the heat gained starts to be lost back into the environment, and this continues until the water in the tank reaches the ambient temperature. The challenge is therefore to limit the heat loss from the tank, thus delaying the time when thermal equilibrium is regained.

## *ICS or batch collectors*

ICS or batch collectors reduce heat loss by placing the water tank in a thermally insulated box. This is achieved by encasing the water tank in a glass-topped box that allows heat from the sun to reach the water tank. However, the other walls of the box are thermally insulated, reducing convection as well as radiation to the environment. In addition, the box can also have a reflective surface on the inside. This reflects heat lost from the tank back towards the tank. In a simple way one could consider an ICS solar water heater as a water tank that has been enclosed in a type of 'oven' that retains heat from the sun as well as heat of the water in the tank. Using a box does not eliminate heat loss from the tank to the environment, but it largely reduces this loss.

## *Standard ICS collectors*

Standard ICS collectors have a characteristic that strongly limits the efficiency of the collector: A small surface-to-volume ratio. Since the amount of heat that a tank can absorb from the sun is largely dependent on the surface of the tank directly exposed to the sun, it follows that a small surface would limit the degree to which the water can be heated by the sun. Cylindrical objects such as the tank in an ICS collector inherently have a small surface-to-volume ratio and most modern collectors attempt to increase this ratio for efficient warming of the water in the tank. There are many variations on this basic design, with some ICS collectors comprising several smaller water containers and even including evacuated glass tube technology, a type of ICS system known as an Evacuated Tube Batch (ETB) collector.

## *Flat-plate collectors*

Flat-plate collectors are an extension of the basic idea to place a collector in an 'oven'-like box with glass in the direction of the sun. Most flat-plate collectors have two horizontal pipes at the top and bottom, called headers, and many smaller vertical pipes connecting them, called risers. The risers are welded (or similarly connected) to thin absorber fins. Heat-transfer fluid (water or water/antifreeze mix) is pumped from the hot water storage tank (direct system) or heat exchanger (indirect system) into the collectors' bottom header, and it travels up the risers, collecting heat from the absorber fins, and then exits the collector out of the top header. Serpentine flat-plate collectors differ slightly from this 'harp' design, and instead use a single pipe that travels up and down the collector. However, since they cannot be properly drained of water, serpentine flat-plate collectors cannot be used in drainback systems. The type of glass used in flat-plate collectors is almost always low-iron, tempered glass. Being tempered, the glass can withstand significant hail without breaking, which is one of the reasons that flat-plate collectors are considered the most durable collector type.

## *Unglazed or formed collectors*

Unglazed or formed collectors are similar to flat-plate collectors, except they are not thermally insulated nor physically protected by a glass panel. Consequently these types of collectors are much less efficient for domestic water heating. For pool heating applications, however, the water being heated is often colder than the ambient roof temperature, at which point the lack of thermal insulation allows additional heat to be drawn from the surrounding environment.

### *Evacuated tube collectors (ETC)*

Evacuated tube collectors are a way in which heat loss to the environment, inherent in flat-plates, has been reduced. Since heat loss due to convection cannot cross a vacuum, it forms an efficient isolation mechanism to keep heat inside the collector pipes. Since two flat sheets of glass are normally not strong enough to withstand a vacuum, the vacuum is rather created between two concentric tubes. Typically, the water piping in an ETC is therefore surrounded by two concentric tubes of glass with a vacuum in between that admits heat from the sun (to heat the pipe) but which limits heat loss back to the environment. The inner tube is coated with a thermal absorbent. Life of the vacuum varies from collector to collector, anywhere from 5 years to 15 years. Flat-plate collectors are generally more efficient than ETC in full sunshine conditions. However, the energy output of flat-plate collectors is reduced slightly more than evacuated tube collectors in cloudy or extremely cold conditions. Most ETCs are made out of annealed glass, which is susceptible to hail, breaking in roughly golf ball-sized hail. ETCs made from ‘coke glass’, which has a green tint, are stronger and less likely to lose their vacuum, but efficiency is slightly reduced due to reduced transparency.

## 4.8 Heating of swimming pools

Both pool covering systems floating atop the water and separate solar thermal collectors may be used for pool heating. Pool covering systems, whether solid sheets or floating disks, act as solar collectors and provide pool heating benefits which, depending on climate, may either supplement the solar thermal collectors discussed below or make them unnecessary.

Solar thermal collectors for nonpotable pool water use are often made of plastic. Pool water, mildly corrosive due to chlorine, is circulated through the panels using the existing pool filter or supplemental pump. In mild environments, unglazed plastic collectors are more efficient as a direct system. In cold or windy environments evacuated tubes or flat-plates in an indirect configuration do not have pool water pumped through them, they are used in conjunction with a heat exchanger that transfers the heat to pool water. This causes less corrosion. A fairly simple differential temperature controller is used to direct the water to the panels or heat exchanger either by turning a valve or operating the pump. Once the pool water has reached the required temperature, a diverter valve is used to return pool water directly to the pool without heating. Many systems are configured as drainback systems where the water drains into the pool when the water pump is switched off. The collector panels are usually mounted on a nearby roof or ground-mounted on a tilted rack. Due to the low temperature difference between the air and the water, the panels are often formed collectors or unglazed flat-plate collectors. A simple rule-of-thumb for the required panel area needed is 50 per cent of the pool's surface area. This is for areas where pools are used in the summer season only, not year round. Adding solar collectors to a conventional outdoor pool, in a cold climate, can typically extend the pool's comfortable usage by some months or more if an insulating pool cover is also used. An active solar energy system analysis program may be used to optimise the solar pool heating system before it is built.

## 4.9 Economics, energy, environment and system costs

### 4.9.1 Energy production

The amount of heat delivered by a solar water heating system depends primarily on the amount of heat delivered by the sun at a particular place (the insolation). In tropical places the insolation can be relatively high, e.g. 7 kWh/m$^2$ per day, whereas the insolation can be much lower in temperate areas where the days are shorter in winter, e.g. 3.2 kWh/m$^2$ per day. Even at the same latitude the average insolation can vary a great deal from location to location due to differences in local weather patterns and the amount of overcast. Useful calculators for estimating insolation at a site can be found with the Joint Research Laboratory of the European Commission and the American National Renewable Energy Laboratory.

Table 4.1 gives a rough indication of the specifications and energy that could be expected from a solar water heating system involving some 2 m$^2$ of absorber area of the collector, demonstrating two evacuated tube and three flat-plate solar water heating systems. Certification information or figures calculated from those data are used. The bottom two rows give estimates for daily energy production (kWh/day) for a tropical and a temperate scenario. These estimates are for heating water to 50°C above ambient temperature. With most solar water heating systems, the energy output scales linearly with the surface area of the absorbers. Therefore, when comparing figures, take into account the absorber area of the collector because collectors with less absorber area yield less heat, even within the 2 m$^2$ range. Specifications for many complete solar water heating systems and separate solar collectors can be found at Internet site of the SRCC.

**Table 4.1** Daily energy production (kW/thh) of five solar thermal systems. Both the evac tube systems used have 20 tubes.

| Technology Configuration | Flat-plate Direct active | Flat-plate Thermosiphon | Flat-plate Indirect active | Evac tube Indirect active | Evac tube Direct active |
|---|---|---|---|---|---|
| Overall size ($m^2$) | 2.49 | 1.98 | 1.87 | 2.85 | 2.97 |
| Absorber size ($m^2$) | 2.21 | 1.98 | 1.72 | 2.85 | 2.96 |
| Maximum efficiency | 0.68 | 0.74 | 0.61 | 0.57 | 0.46 |
| Energy production (kWh/day)<br>Insolation 3.2 kWh/ $m^2$/day<br>(temperate)<br>e.g. Zurich, Switzerland | 5.3 | 3.9 | 3.3 | 4.8 | 4.0 |
| Insolation 6.5 kWh/ $m^2$/day<br>(tropical)<br>e.g. Phoenix, USA | 11.2 | 8.8 | 7.1 | 9.9 | 8.4 |

The figures are fairly similar between the above collectors, yielding some 4 kWh/day in a temperate climate and some 8 kWh/day in a more tropical climate when using a collector with an absorber area of about 2 $m^2$ in size. In the temperate scenario this is sufficient to heat 200 litres of water by some 17°C. In the tropical scenario the equivalent heating would be by some 33°C. Many thermosiphon systems are quite efficient and have comparable energy output to equivalent active systems. The efficiency of evacuated tube collectors is somewhat lower than for flat plate collectors because the absorbers are narrower than the tubes and the tubes have space between them, resulting in a significantly larger percentage of inactive overall collector area. Some methods of comparison calculate the efficiency of evacuated tube collectors based on the actual absorber area and not on the ‘roof area’ of the system as has been done in the above table. The efficiency of the collectors becomes lower if one demands water with a very high temperature.

### 4.9.2 System cost

In sunny, warm locations, where freeze protection is not necessary, an ICS (batch type) solar water heater can be extremely cost effective. In higher latitudes, there are often additional design requirements for cold weather, which add to system complexity. This has the effect of increasing the initial cost (but not the life-cycle cost) of a solar water heating system, to a level much higher than a comparable hot water heater of the conventional type. The biggest single consideration is therefore the large initial financial outlay of solar water heating systems. Offsetting this expense can take several years and the payback period is longer in temperate environments where the insolation is less intense. When calculating the total cost to own and operate, a proper analysis will consider that solar energy is free, thus greatly reducing the operating costs, whereas other energy sources, such as gas and electricity, can be quite expensive over time. Thus, when the initial costs of a solar system are properly financed and compared with energy costs, then in many cases the total monthly cost of solar heat can be less than other more conventional types of hot water heaters (also in conjunction with an existing hot water heater). At higher latitudes, solar heaters may be less effective due to lower solar energy, possibly requiring larger and/or dual-heating systems.

The calculation of long term-cost and payback period for a household SWH system depends on a number of factors. Some of these are:

1. Price of purchasing solar water heater (more complex systems are more expensive)
2. Efficiency of SWH system purchased
3. Installation cost
4. State or government subsidy for installation of a solar water heater
5. Price of electricity per kWh
6. Number of kWh of electricity used per month by a household
7. Annual tax rebates or subsidy for using renewable energy
8. Annual maintenance cost of SWH system
9. Savings in annual maintenance of conventional (electric/gas/oil) water heating system

### *Operational carbon/energy footprint and life-cycle assessment*

*Terminology*

1. Operational energy footprint (OEF) is also called energy parasitics ratio (EPR) or coefficient of performance (CoP).
2. Operational carbon footprint (OCF) is also called carbon clawback ratio (CCR).
3. Life-cycle assessment is usually referred to as LCA.

## 4.9.3 Carbon/energy footprint

The source of electricity in an active SWH system determines the extent to which a system contributes to atmospheric carbon during operation. Active solar thermal systems that use mains electricity to pump the fluid through the panels are called ‘low carbon solar’. In most systems the pumping cancels the energy savings by about 8 per cent and the carbon savings of the solar by about 20 per cent. However, some new low power pumps will start operation with 1 W and use a maximum of 20 W. Assuming a solar collector panel delivering 4 kWh/day and a pump running intermittently from mains electricity for a total of 6 hours during a 12-hour sunny day, the potentially negative effect of such a pump can be reduced to about 3 per cent of the total power produced.

The carbon footprint of such household systems varies substantially, depending on whether electricity or other fuels such as natural gas are being displaced by the use of solar. Except where a high proportion of electricity is already generated by non-fossil fuel means, natural gas, a common water heating fuel, in many countries, has typically only about 40 per cent of the carbon intensity of mains electricity per unit of energy delivered. Therefore the 3 per cent or 8 per cent energy clawback in a gas home referred to above could therefore be considered 8 per cent to 20 per cent carbon clawback, a very low figure compared to technologies such as heat pumps. However, PV-powered active solar thermal systems typically use a 5–30 W PV panel which faces in the same direction as the main solar heating panel and a small, low power diaphragm pump or centrifugal pump to circulate the water. This reduces the operational carbon and energy footprint: a growing design goal for solar thermal systems.

Work is also taking place in a number of parts of the world on developing alternative non-electrical pumping systems. These are generally based on thermal expansion and phase changes of liquids and gases, a variety of which are under development.

## *Life-cycle carbon/energy assessment*

Now looking at a wider picture than just the operational environmental impacts, recognised standards can be used to deliver robust and quantitative life-cycle assessment (LCA). LCA takes into account the total environmental cost of acquisition of raw materials, manufacturing, transport, using, servicing and disposing of the equipment. There are several aspects to such an assessment, including:

1. The financial costs and gains incurred during the life of the equipment.
2. The energy used during each of the above stages.
3. The $CO_2$ emissions due to each of the above stages.

Each of these aspects may present different trends with respect to a specific SWH device.

## *Financial assessment*

Table 4.1 in the previous section as well as several other studies suggest that the cost of production is gained during the first 5–12 years of use of the equipment, depending on the insolation, with cost efficiency increasing as the insolation does.

In terms of energy, some 60 per cent of the materials of a SWH system go into the tank, with some 30 per cent towards the collector (thermosiphon flat plate in this case). In Italy, some 11 GJ of electricity are used in producing the equipment, with about 35 per cent of the energy going towards the manufacturing the tank, with another 35 per cent towards the collector and the main energy-related impact being emissions. The energy used in manufacturing is recovered within the first two to three years of use of the SWH system through heat captured by the equipment.

Moving further north into colder, less sunny climates, the energy payback time of a solar water heating system in a UK climate is reported as only 2 years. This figure was derived from the studied solar water heating system being: direct, retrofitted to an existing water store, PV pumped, freeze tolerant and of 2.8 sq m aperture. For comparison, a solar electric (PV) installation took around 5 years to reach energy payback, according to the same comparative study.

In terms of $CO_2$ emissions, a large degree of the emissions-saving traits of a SWH system is dependent on the degree to which water heating by gas or electricity is used to supplement solar heating of water. Using the Eco-indicator 99 points system as a yardstick (i.e. the yearly environmental load of an average European inhabitant) in Greece, a purely gas-driven system may be cheaper in terms of emissions than a solar system. This calculation assumes that the solar system produces about half of the hot water requirements of a household. The production of a test SWH system in Italy produced about 700 kg of $CO_2$, with all the components of manufacture, use and disposal contributing small parts towards this. Maintenance was identified as an emissions-costly activity when the heat transfer fluid (glycol-based) was periodically replaced. However, the emissions cost was recovered within about two years of use of the equipment through the emissions saved by solar water heating. In Australia, the life-cycle emissions of a SWH system are also recovered fairly rapidly, where a SWH system has about 20 per cent of the impact of an electrical water heater and half of the emissions impact of a gas water heater.

Analysing their lower impact retrofit solar water heating system, Allen (qv) report a production of $CO_2$ impact of 337 kg, which is around half the environmental impact reported in the Ardente (qv) study.

Where information based on established standards are available, the environmental transparency afforded by life-cycle analysis allows consumers (of all products) to make increasingly well-informed product selection decisions. As for identifying sectors where this information is likely to appear first, environmental technology suppliers in the microgeneration and renewable energy technology arena are increasingly being pressed by consumers to report typical CoP and LCA figures for their products.

In summary, the energy and emissions cost of a SWH system forms a small part of the life-cycle cost and can be recovered fairly rapidly during use of the equipment. Their environmental impacts can be reduced further by sustainable materials sourcing, using non-mains circulation, by reusing existing hot water stores and, in cold climates, by eliminating antifreeze replacement visits.

## 4.10 Do-It-Yourself (DIY) systems

People have begun building their own (small-scale) solar water heating systems from scratch or buying kits. Plans for solar water heating systems are available on the Internet, and people have set about building them for their own domestic requirements. DIY SWH systems are usually cheaper than commercial ones, and they are used both in the developed and developing world.

### 4.10.1 System specification and installation

1. Except in rare instances, it will be insufficient to install a SWH system with no electrical or gas or other fuel backup. Many SWH systems have a back-up electric heating element in the integrated tank, the operation of which may be necessary on cloudy days to ensure a reliable supply of hot water.
2. The temperature stability of a system is dependent on the ratio of the volume of warm water used per day as a fraction of the size of the water reservoir/tank that stores the hot water. If a large proportion of hot water in the reservoir is used each day, a large fraction of the water in the reservoir needs to be heated. This brings about significant fluctuations in water temperature every day, with possible risks of overheating or underheating, depending on the design of the system. Since the amount of heating that needs to take place every day is proportional to hot water usage and not to the size of the reservoir, it is desirable to have a fairly large reservoir (i.e. equal to or greater than daily usage), which will help prevent fluctuations in water temperature.

3. If ample storage is pre-existing or can otherwise be reasonably acquired, a large SWH system is more efficient economically than a small system. This is because the price of a system is not linearly proportional to the size of the collector array, so the price per square metre of collector is cheaper in a larger system. If this is the case, it pays to use a system that covers nearly all of the domestic hot water needs, and not only a small fraction of the needs. This facilitates more rapid cost recovery.
4. Not all installations require new replacement solar hot water stores. Existing stores may be large enough and in suitable condition. Direct systems can be retrofitted to existing stores, while indirect systems can be also sometimes be retrofitted using internal and external heat exchangers.
5. The installation of a SWH system needs to be complemented with efficient insulation of all the water pipes connecting the collector and the water storage tank, as well as the storage tank (or 'geyser') and the most important warm water outlets. The installation of efficient lagging significantly reduces the heat loss from the hot water system. The installation of lagging on at least two metres of pipe on the cold water inlet of the storage tank reduces heat loss, as does the installation of a 'geyser blanket' around the storage tank (if inside a roof). In cold climates the installation of lagging and insulation is often performed even in the absence of a SWH system.
6. The most efficient PV pumps are designed to start very slowly in very low light levels, so if connected uncontrolled, they may cause a small amount of unwanted circulation early in the morning—for example when there is enough light to drive the pump but while the collector is still cold. To eliminate the risk of hot water in the storage tank from being cooled that way this is very important. Solar controller may be required.
7. The modularity of an evacuated tube collector array allows the adjustment of the collector size by removing some tubes or their heat pipes. Budgeting for a larger than required array of tubes therefore allows for the customisation of collector size to the needs of a particular application, especially in warmer climates.
8. Particularly in locations further towards the poles than 45 degrees from the equator, roof mounted sun facing collectors tend to outperform wall mounted collectors in terms of total energy output. However it is total useful energy output which usually matters most to consumers. So arrays of sunny wall mounted steep collectors can sometimes produce more useful energy because there can be a small increase in winter gain at the expense of a large unused summer surplus.

## 4.11 Solar tracker

A solar tracker is a generic term used to describe devices that orient various payloads toward the sun. Payloads can be photovoltaic panels, reflectors, lenses or other optical devices. In flat-panel photovoltaic (PV) applications trackers are used to minimise the angle of incidence between the incoming light and a photovoltaic panel. This increases the amount of energy produced from a fixed amount of installed power generating capacity. In standard photovoltaic applications, it is estimated that trackers are used in at least 85 per cent of commercial installations greater than 1 MW from 2009 to 2012.

In concentrated photovoltaic (CPV) and CSP applications trackers are used to enable the optical components in the CPV and CSP systems. The optics in concentrated solar applications accepts the direct component of sunlight and therefore must be oriented appropriately to collect energy. Tracking systems are found in all concentrator applications because such systems do not produce energy unless oriented closely toward the sun.

### 4.11.1 Types of solar collector

Different types of solar collector and their location (latitude) require different types of tracking mechanism. Solar collectors may be:

1. Non-concentrating flat-panels, usually photovoltaic or hot-water
2. Concentrating systems, of a variety of types

Solar collector mounting systems may be fixed (manually aligned) or tracking. Tracking systems may be configured as:

1. Fixed collector/moving mirror, i.e. Heliostat
2. Moving collector

#### *Fixed mount*

Domestic and small-scale commercial photovoltaic and hot-water panels are usually fixed, often flush-mounted on an appropriately facing pitched roof. Advantages of fixed mount systems (i.e. factors tending to indicate against trackers) include the following:

1. Mechanical simplicity, and hence lower installation and ongoing maintenance costs.
2. Wind-loading: It is easier and cheaper to provision a sturdy mount; all mounts other than fixed flush-mounted panels must be carefully designed having regard to their wind loading due to their greater exposure.
3. Indirect light: Approximately 10 per cent of the incident solar radiation is diffuse light, available at any angle of misalignment with the direct sun.

4. Tolerance to misalignment: Effective collection area for a flat-panel is relatively insensitive to quite high levels of misalignment with the sun (Table 4.2 and Fig. 4.5) at Accuracy Requirements section below—for example even a 25° misalignment reduces the direct solar energy collected by less than 10 per cent.

Fixed mounts are usually used in conjunction with non-concentrating systems, however an important class of non-tracking concentrating collectors, of particular value in the 3rd world, are portable solar cookers. These utilise relatively low levels of concentration, typically around 2 to 8 suns and are manually aligned.

**Table 4.2** Direct power lost ( per cent) due to misalignment (angle i).

| i | Lost | i | Hours | Lost |
|---|---|---|---|---|
| 0° | 0% | 15° | 1 | 3.4% |
| 1° | 0.015% | 30° | 2 | 13.4% |
| 3° | 0.14% | 45° | 3 | 30% |
| 8° | 1% | 60° | 4 | >50% |
| 23.4° | 8.3% | 75° | 5 | >75% |

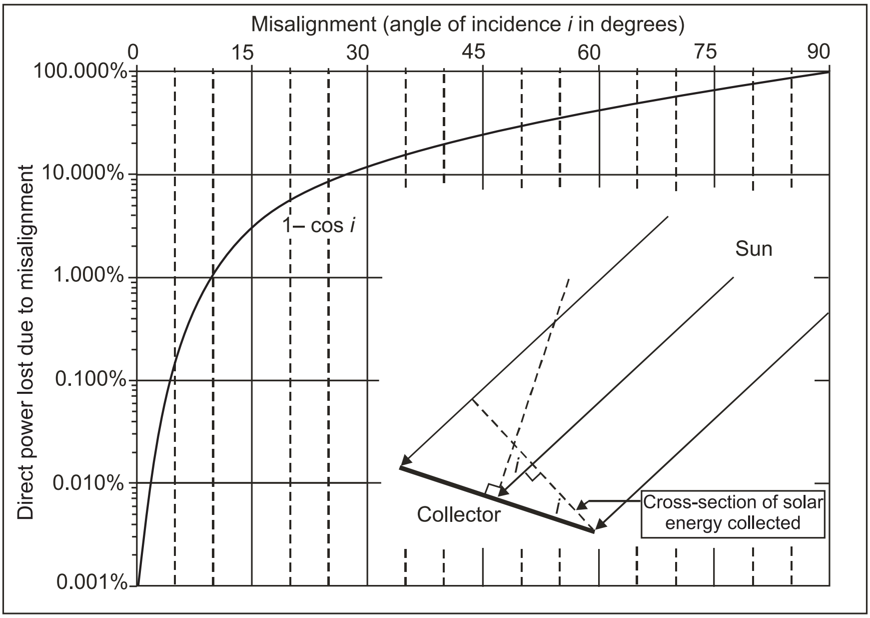



**Figure 4.5** The effective collection area of a flat-panel solar collector varies with the cosine of the misalignment of the panel with the sun.

### *Trackers*

Even though a fixed flat-panel can be set to collect a high proportion of available noon-time energy, significant power is also available in the early mornings and late afternoons when the misalignment with a fixed panel becomes excessive to collect a reasonable proportion of the available energy. For example, even when the sun is only 10° above the horizon the available energy can already be around half the noon-time energy levels (or even greater depending on latitude, season, and atmospheric conditions).

Thus the primary benefit of a tracking system is to collect solar energy for the longest period of the day, and with the most accurate alignment as the sun's position shifts with the seasons.

In addition, the greater the level of concentration employed the more important accurate tracking becomes, because the proportion of energy derived from direct radiation is higher, and the region where that concentrated energy is focused becomes smaller.

### *Fixed collector/moving mirror*

Many collectors cannot be moved, for example high-temperature collectors where the energy is recovered as hot liquid or gas (e.g. steam). Other examples include direct heating and lighting of buildings and fixed in-built solar cookers, such as Scheffler reflectors. In such cases it is necessary to employ a moving mirror so that, regardless of where the sun is positioned in the sky, the sun's rays are redirected onto the collector. Due to the complicated motion of the sun across the sky, and the level of precision required to correctly aim the sun's rays onto the target, a heliostat mirror generally employs a dual axis tracking system, with at least one axis mechanised. In different applications, mirrors may be flat or concave.

### *Moving collector*

Trackers can be grouped into classes by the number and orientation of the tracker's axes. Compared to a fixed mount, a single axis tracker increases annual output by approximately 30 per cent, and a dual axis tracker an additional 6 per cent. Photovoltaic trackers can be classified into two types: Standard Photovoltaic (PV) Trackers and Concentrated Photovoltaic (CPV) Trackers. Each of these tracker types can be further categorised by the number and orientation of their axes, their actuation architecture and drive type, their intended applications, their vertical supports and foundation type. Solar tracking systems are mostly used in Bangladesh.

## 4.11.2 Non-concentrating photovoltaic (PV) trackers

Photovoltaic panels accept both direct and diffuse light from the sky. The panels on a standard photovoltaic trackers always gather the available direct light. The tracking functionality in standard photovoltaic trackers is used to minimise the angle of incidence between incoming light and the photovoltaic panel. This increases the amount of energy gathered from the direct component of the incoming light.

### *Accuracy requirements*

In non-concentrating flat-panel systems, the energy contributed by the direct beam drops off with the cosine of the angle between the incoming light and the panel. In addition, the reflectance (averaged across all polarisations) is approximately constant for angles of incidence up to around 50°, beyond which reflectance degrades rapidly. For example trackers that have accuracies of ±5° can deliver greater than 99.6 per cent of the energy delivered by the direct beam plus 100 per cent of the diffuse light. As a result, high accuracy tracking is not typically used in non-concentrating PV applications.

### *Technologies supported*

The physics behind standard photovoltaic (PV) trackers works with all standard photovoltaic module technologies. These include all types of crystalline silicon panels (monocrystalline, multicrystalline, polycrystalline) and all types of thin film panels (amorphous silicon, CdTe, CIGS, microcrystalline).

## 4.11.3 Concentrated photovoltaic (CPV) trackers

The optics in CPV modules accept the direct component of the incoming light and therefore must be oriented appropriately to maximise the energy collected. In low concentration applications a portion of the diffuse light from the sky can also be captured. The tracking functionality in CPV modules is used to orient the optics such that the incoming light is focused to a photovoltaic collector.

CPV modules that concentrate in one dimension must be tracked normal to the sun in one axis. CPV modules that concentrate in two dimensions must be tracked normal to the sun in two axes.

### *Accuracy requirements*

The physics behind CPV optics requires that tracking accuracy increase as the systems concentration ratio increases. However, for a given concentration, non-imaging optics provides the widest possible acceptance angles, which may be used to reduce tracking accuracy.

In typical high concentration systems tracking accuracy must be in the ±0.1° range to deliver approximately 90 per cent of the rated power output. In low concentration systems, tracking accuracy must be in the ±2.0° range to deliver 90 per cent of the rated power output. As a result, high accuracy tracking systems are typically used.

### *Technologies supported*

Concentrated photovoltaic trackers are used with refractive and reflective based concentrator systems. There is a range of emerging photovoltaic cell technologies used in these systems. These range from crystalline silicon are based on photovoltaic receivers to germanium based triple junction receivers.

## 4.11.4 Single axis trackers

Single axis trackers have one degree of freedom that acts as an axis of rotation. The axis of rotation of single axis trackers is typically aligned along a true North meridian. It is possible to align them in any cardinal direction with advanced tracking algorithms.

There are several common implementations of single axis trackers. These include horizontal single axis trackers (HSAT), vertical single axis trackers (VSAT), tilted single axis trackers (TSAT) and polar aligned single axis trackers (PSAT). The orientation of the module with respect to the tracker axis is important when modelling performance.

### *Horizontal single axis tracker (HSAT)*

The axis of rotation for horizontal single axis tracker is horizontal with respect to the ground. The posts at either end of the axis of rotation of a horizontal single axis tracker can be shared between trackers to lower the installation cost. Field layouts with horizontal single axis trackers are very flexible. The simple geometry means that keeping all the axis of rotation parallel to one another is all that is required for appropriately positioning the trackers with respect to one another.

Appropriate spacing can maximise the ratio of energy production to cost, this being dependent upon local terrain and shading conditions and the time-of-day value of the energy produced. Backtracking is one means of computing the disposition of panels. Horizontal trackers typically have the face of the module oriented parallel to the axis of rotation. As a module tracks, it sweeps a cylinder that is rotationally symmetric around the axis of rotation.

Several manufacturers can deliver single axis horizontal trackers. In these, a long horizontal tube is supported on bearings mounted upon pylons or frames. The axis of the tube is on a north-south line. Panels are mounted upon the tube, and the tube will rotate on its axis to track the apparent motion of the sun through the day.

### *Vertical single axis tracker (VSAT)*

The axis of rotation for vertical single axis trackers is vertical with respect to the ground. These trackers rotate from East to West over the course of the day. Such trackers are more effective at high latitudes than are horizontal axis trackers.

Field layouts must consider shading to avoid unnecessary energy losses and to optimise land utilisation. Also optimisation for dense packing is limited due to the nature of the shading over the course of a year.

Vertical single axis trackers typically have the face of the module oriented at an angle with respect to the axis of rotation. As a module tracks, it sweeps a cone that is rotationally symmetric around the axis of rotation.

### *Tilted single axis tracker (TSAT)*

All trackers with axes of rotation between horizontal and vertical are considered tilted single axis trackers. Tracker tilt angles are often limited to reduce the wind profile and decrease the elevated end's height off the ground. Field layouts must consider shading to avoid unnecessary losses and to optimise land utilisation. With backtracking, they can be packed without shading perpendicular to their axis of rotation at any density. However, the packing parallel to their axis of rotation is limited by the tilt angle and the latitude. Tilted single axis trackers typically have the face of the module oriented parallel to the axis of rotation. As a module tracks, it sweeps a cylinder that is rotationally symmetric around the axis of rotation.

### *Polar-aligned single axis trackers (PASAT)*

One scientifically interesting variation of a tilted single axis tracker is a polar-aligned single axis trackers (PASAT). In this particular implementation of a tilted single axis tracker the tilt angle is equal to the latitude of the installation. This aligns the tracker axis of rotation with the earth's axis of rotation. These are rarely deployed because of their high wind profile.

## 4.11.5 Dual axis trackers

Dual axis trackers have two degrees of freedom that act as axes of rotation. These axes are typically normal to one another. The axis that is fixed with respect to the ground can be considered a primary axis. The axis that is referenced to the primary axis can be considered a secondary axis.

There are several common implementations of dual axis trackers. They are classified by the orientation of their primary axes with respect to the ground. Two common implementations are tip–tilt dual axis trackers (TTDAT) and azimuth-altitude dual axis trackers (AADAT). The orientation of the module with respect to the tracker axis is important when modelling performance. Dual axis trackers typically have modules oriented parallel to the secondary axis of rotation. Dual axis trackers allow for optimum solar energy levels due to their ability to follow the sun vertically and horizontally. No matter where the sun is in the sky, dual axis trackers are able to angle themselves to be in direct contact with the sun.

### *Tip–tilt dual axis tracker (TTDAT)*

A tip–tilt dual axis tracker has its primary axis horizontal to the ground. The secondary axis is then typically normal to the primary axis. The posts at either end of the primary axis of rotation of a tip–tilt dual axis tracker can be shared between trackers to lower installation costs.

Field layouts with tip–tilt dual axis trackers are very flexible. The simple geometry means that keeping the axes of rotation parallel to one another is all that is required for appropriately positioning the trackers with respect to one another. In addition, with backtracking, they can be packed without shading at any density. The axes of rotation of tip–tilt dual axis trackers are typically aligned either along a true North meridian or an east-west line of latitude. It is possible to align them in any cardinal direction with advanced tracking algorithms.

### *Azimuth-altitude dual axis tracker (AADAT)*

An azimuth–altitude dual axis tracker has its primary axis vertical to the ground. The secondary axis is then typically normal to the primary axis. Field layouts must consider shading to avoid unnecessary energy losses and to optimise land utilisation. Also optimisation for dense packing is limited due to the nature of the shading over the course of a year. This mount is used as a large telescope mount owing to its structure and dimensions. One axis is a vertical pivot shaft or horizontal ring mount that allows the device to be swung to a compass point. The second axis is a horizontal elevation pivot mounted upon the azimuth platform. By using combinations of the two axis, any location in the upward hemisphere may be pointed. Such systems may be operated under computer control according to the expected solar orientation or may use a tracking sensor to control motor drives that orient the panels toward the sun. This type of mount is also used to orient parabolic reflectors that mount a Stirling engine to produce electricity at the device.

### 4.11.6 Tracker type selection

The selection of tracker type is dependent on many factors including installation size, electric rates, government incentives, land constraints, latitude, and local weather. Horizontal single axis trackers are typically used for large distributed generation projects and utility scale projects. The combination of energy improvement and lower product cost and lower installation complexity results in compelling economics in large deployments. In addition the strong afternoon performance is particularly desirable for large grid-tied photovoltaic systems so that production will match the peak demand time. Horizontal single axis trackers also add a substantial amount of productivity during the spring and summer seasons when the sun is high in the sky. The inherent robustness of their supporting structure and the simplicity of the mechanism also result in high reliability which keeps maintenance costs low. Since the panels are horizontal, they can be compactly placed on the axle tube without danger of self-shading and are also readily accessible for cleaning. A vertical axis trackers pivots only about a vertical axle, with the panels either vertical, at a fixed, adjustable or tracked elevation angle. Such trackers with fixed or (seasonably) adjustable angles are suitable for high latitudes, where the apparent solar path is not especially high, but which leads to long days in summer, with the sun travelling through a long arc. Dual axis trackers are typically used in smaller residential installations and locations with very high government feed-in tariffs.

### 4.11.7 Multi-mirror concentrating PV

This device uses multiple mirrors in a horizontal plane to reflect sunlight upward to a high temperature photovoltaic or other system requiring concentrated solar power. Structural problems and expense are greatly reduced since the mirrors are not significantly exposed to wind loads. Through the employment of a patented mechanism, only two drive systems are required for each device. Because of the configuration of the device it is especially suited for use on flat roofs and at lower latitudes. The units illustrated each produce approximately 200 peak DC watts. A multiple mirror reflective system combined with a central power tower is employed at the Sierra Sun Tower, located in Lancaster, California. This system, which uses multiple heliostats in a north–south alignment, uses pre-fabricated parts and construction as a way of decreasing start-up and operating costs.

### 4.11.8 Drive types

#### *Active tracker*

Active trackers use motors and gear trains to direct the tracker as commanded by a controller responding to the solar direction. In order to control and manage the movement of these massive structures special slewing drives are designed and rigorously tested. Active two-axis trackers are also used to orient heliostats-moveable mirrors that reflect sunlight toward the absorber of a central power station. As each mirror in a large field will have an individual orientation these are controlled programmatically through a central computer system, which also allows the system to be shut down when necessary. Light-sensing trackers typically have two photosensors, such as photodiodes, configured differentially so that they output a null when receiving the same light flux. Mechanically, they should be omnidirectional (i.e. flat) and are aimed 90° apart.

This will cause the steepest part of their cosine transfer functions to balance at the steepest part, which translates into maximum sensitivity. Since the motors consume energy, one wants to use them only as necessary. So instead of a continuous motion, the heliostat is moved in discrete steps. Also, if the light is below some threshold there would not be enough power generated to warrant reorientation. This is also true when there is not enough difference in light level from one direction to another, such as when clouds are passing overhead. Consideration must be made to keep the tracker from wasting energy during cloudy periods.

#### *Passive tracker*

Passive trackers use a low boiling point compressed gas fluid that is driven to one side or the other (by solar heat creating gas pressure) to cause the tracker to move in response to an imbalance. As this is a non-precision orientation it is unsuitable for certain types of concentrating photovoltaic collectors but works fine for common PV panel types. These will have viscous dampers to prevent excessive motion in response to wind gusts. Shader/reflectors are used to reflect early morning sunlight to ‘wake up’ the panel and tilt it toward the sun, which can take nearly an hour. The time to do this can be greatly reduced by adding a self-releasing tie down that positions the panel slightly past the zenith (so that the fluid does not have to overcome gravity) and using the tie down in the evening. (A slack-pulling spring will prevent release in windy overnight conditions.)

The term ‘passive tracker’ is also used for photovoltaic modules that include a hologram behind stripes of photovoltaic cells. That way, sunlight passes through the transparent part of the module and reflects on the hologram. This allows sunlight to hit the cell from behind, thereby increasing the module's efficiency. Also, the module does not have to move since the hologram always reflects sunlight from the correct angle towards the cells.

### *Chronological tracker*

A chronological tracker counteracts the earth's rotation by turning at an equal rate as the earth, but in the opposite direction. Actually the rates are not quite equal, because as the earth goes around the sun, the position of the sun changes with respect to the earth by 360° every year or 365.24 days. A chronological tracker is a very simple yet potentially a very accurate solar tracker specifically for use with a polar mount. The drive method may be as simple as a gear motor that rotates at a very slow average rate of one revolution per day (15° per hour). In theory the tracker may rotate completely, assuming there is enough clearance for a complete rotation, and assuming that twisting wires are not an issue.

## 4.12 Photovoltaic thermal hybrid solar collector

Photovoltaic thermal hybrid solar collectors, sometimes known as hybrid PV/T systems or PVT, are systems that convert solar radiation into thermal and electrical energy. These systems combine a photovoltaic cell, which converts electromagnetic radiation (photons) into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module. Photovoltaic (PV) cells suffer from a drop in efficiency with the rise in temperature due to increased resistance. Such systems can be engineered to carry heat away from the PV cells thereby cooling the cells and thus improving their efficiency by lowering resistance.

### 4.12.1 System types

A number of PV/T collectors in different categories are commercially available and can be divided into the following categories:

1. PV/T liquid collector
2. PV/T air collector
3. PV/T concentrator (CPVT)

### *PV/T liquid collector*

The basic water-cooled design uses conductive-metal piping or plates attached to the back of a PV module. A working fluid, typically water, glycol or mineral oil is then piped through these pipes. The heat from the PV cells are conducted through the metal and absorbed by the working fluid (presuming that the working fluid is cooler than the operating temperature of the cells). In closed-loop systems this heat is either exhausted (to cool it) or transferred at a heat exchanger, where it flows to its application. In open-loop systems, this heat is used or exhausted before the fluid returns to the PV cells.

### *PV/T concentrator (CPVT)*

A concentrating system has the advantage to reduce the amount of solar cells needed. It also can get very good solar thermal performance compared to flat PV/T collectors. The main obstacles are to provide good cooling of the solar cells and a durable tracking system.

## 4.13 Solar furnace

A solar furnace is a structure that captures sunlight to produce high temperatures, usually for industry. This is done with a curved mirror (or an array of mirrors) that acts as a parabolic reflector, concentrating light (Insolation) onto a focal point. The temperature at the focal point may reach 3500°C (6330°F), and this heat can be used to generate electricity, melt steel, make hydrogen fuel or nanomaterials.

The term ‘solar furnace’ has also evolved to refer to solar concentrator heating systems using parabolic mirrors or heliostats where 538°C is now commonly achieved. The largest solar furnace is at Odeillo in the Pyrénées-Orientales in France, opened in 1970. It employs an array of plane mirrors to gather sunlight, reflecting it onto a larger curved mirror. The rays are then focused onto an area the size of a cooking pot and can reach 3500°C, depending on the process installed, for example:

1. About 1000°C for metallic receivers producing hot air for the next generation solar towers as it will be tested at the Themis plant with the Pegase project.
2. About 1400°C to produce hydrogen by cracking methane molecules.
3. Up to 2500°C to test materials for extreme environment such as nuclear reactors or space vehicle atmospheric re-entry.
4. Up to 3500°C to produce nanomaterials by solar induced sublimation and controlled cooling, such as carbon nanotubes or zinc nanoparticles.

### 4.13.1 Modern uses

The solar furnace principle is being used to make inexpensive solar cookers and solar-powered barbecues, and for solar water pasteurisation. A prototype

Scheffler reflector is being constructed in India for use in a solar crematorium. This 50 $m^2$ reflector will generate temperatures of 700°C (1292°F) and displace 200–300 kg of firewood used per cremation. It has been suggested that solar furnaces could be used in space to provide energy for manufacturing purposes. Their reliance on sunny weather is a limiting factor as a source of renewable energy on earth but could be tied to thermal energy storage systems for energy production through these periods and into the night.

# 5

# Solar photovoltaic systems

## 5.1 Introduction

Photovoltaic devices use semiconducting materials to convert sunlight directly into electricity. It was first observed in 1839 by the French scientist Becquerel who detected that when light was directed onto one side of a simple battery cell, the current generated could be increased. In the late 1950s, the space program provided the impetus for the development of crystalline silicon solar cells. The first commercial production of photovoltaic modules for terrestrial applications began in 1953 with the introduction of automated photovoltaic production plants.

Conventional photovoltaic cells are made of crystalline silicon that has atoms arranged in a three- dimensional array, making it an efficient semiconductor. While this material is most commonly used in converting light energy into electricity, it has associated drawbacks, like high material costs for silicon, costly processes for purifying silicon and manufacturing wafer, additional processes for assembly of modules, and bulky and rigid nature of the photovoltaic panels.

Photovoltaic cells convert sunlight directly into electricity without creating any air or water pollution. Photovoltaic cells are made of at least two layers of semiconductor material. One layer has a positive charge, the other negative. When light enters the cell, some of the photons from the light are absorbed by the semiconductor atoms, freeing electrons from the cell's negative layer to flow through an external circuit and back into the positive layer. This flow of electrons produces electric current. To increase their utility, a number of individual photovoltaic cells are interconnected together in a sealed, weatherproof package called a module (Fig. 5.1). When two modules are wired together in series, their voltage is doubled while the current stays constant. When two modules are wired in parallel, their current is doubled while the voltage stays constant. To achieve the desired voltage and current, modules are wired in series and parallel into what is called a PV array. The flexibility of the modular PV system allows designers to create solar power systems that can meet a wide variety of electrical needs, no matter how large or small.

Photovoltaic modules are usually installed on special ground or pole mounting structures. Modules may be mounted on rooftops provided that proper building and safety precautions are observed. For more output, modules are sometimes installed on a tracker—a mounting structure that moves to continually face the sun throughout the day.

The performance of photovoltaic modules and arrays are generally rated according to their maximum DC power output under standard test conditions (STC). Standard test conditions are defined by a module operating temperature of 250°C, and incident solar irradiance level of 1000 W/m$^2$ and under air mass 1.5 spectral distribution. Since these conditions are not always typical of how PV modules and arrays operate in the field, actual performance is usually 85–90 per cent of the STC rating.

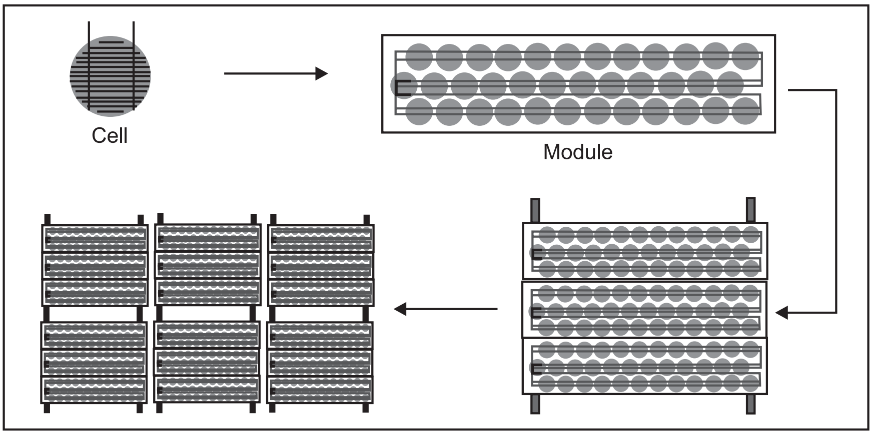



**Figure 5.1** Photovoltaic cells, modules, panels and arrays

## 5.2 Fabrication of photovoltaic cells

### 5.2.1 Silicon-based photovoltaic cells

The process of fabricating conventional single and polycrystalline silicon photovoltaic cells begins with very pure semiconductor-grade polysilicon—a material processed from quartz and used extensively throughout the electronics industry. The polysilicon is then heated to melting temperature, and trace amounts of boron are added to the melt to create a p-type semiconductor material. Next, an ingot or block of silicon is formed, commonly using one of two methods: (i) by growing a pure crystalline silicon ingot from a seed crystal drawn from the molten polysilicon, and (ii) by casting the molten polysilicon in a block, creating a polycrystalline silicon material. Individual wafers are then sliced from the ingots using wire saws and then subjected to a surface etching process. After the wafers are cleaned, they are placed in a phosphorus diffusion furnace, creating a thin n-type semiconductor layer around the entire outer surface of the cell. Next, an anti-reflective coating is applied to the top surface of the cell, and electrical contacts are imprinted on the top (negative) surface of the cell. An aluminised conductive material is deposited on the back (positive) surface of each cell, restoring the p-type properties of the back surface by displacing the diffused phosphorus layer. Each cell is then electrically tested, sorted based on current output, and electrically connected to other cells to form cell circuits for assembly in PV modules.

### 5.2.2 Band gap energies of semiconductors

When light shines on crystalline silicon, electrons within the crystal lattice may be freed. But not all photons, only photons with a certain level of energy can free electrons in the semiconductor material from their atomic bonds to produce an electric current. This level of energy, known as the 'band gap energy', is the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit. To free an electron, the energy of a photon must be at least as great as the band gap energy. However, photons with more energy than the band gap energy will expend that extra amount as heat when freeing electrons. So, it is important for a photovoltaic cell to be 'tuned' through slight modifications to the silicon's molecular structure to optimise the photon energy. A key to obtaining an efficient PV cell is to convert as much sunlight as possible into electricity. Crystalline silicon has band gap energy of 1.1 eV. The band gap energies of other effective photovoltaic semiconductors range from 1.0 to 1.6 eV. In this range, electrons can be freed without creating extra heat. The photon energy of light varies according to the different wavelengths of the light. The entire spectrum of sunlight, from infrared to ultraviolet, covers a range of about 0.5 eV to about 2.9 eV. For example, red light has energy of about 1.7 eV, and blue light has energy of about 2.7 eV. Most PV cells cannot use about 55 per cent of the energy of sunlight, because this energy is either below the band gap of the material or carries excess energy.

### 5.2.3 Doping silicon to create n-type and p-type silicon

In a crystalline silicon cell, we need to contact p-type silicon with n-type silicon to create the built-in electrical field. The process of doping, which creates these materials, introduces an atom of another element into the silicon crystal to alter its electrical properties. The dopant, which is the introduced element, has either three or five valence electrons, which is one less or one more that silicon's four.

Phosphorus atoms, which have five valence electrons, are used in doping n-type silicon, because phosphorus provides its fifth free electron. A phosphorus atom occupies the same place in the crystal lattice formerly occupied by the silicon atom it replaces (Fig. 5.2). Four of its valence electrons take over the bonding responsibilities of the four silicon valence electrons that they replaced. But the fifth valence electron remains free, having no bonding responsibilities. When phosphorus atoms are substituted for silicon in a crystal, many free electrons become available.

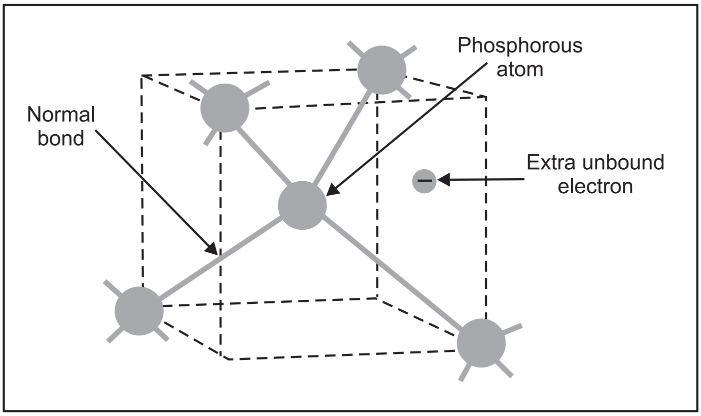



**Figure 5.2** Phosphorus substituted n-type silicon

The most common method of doping is to coat a layer of silicon material with phosphorus and then heat the surface. This allows the phosphorus atoms to diffuse into the silicon. The temperature is then reduced so the rate of diffusion drops to zero. Other methods of introducing phosphorus into silicon include gaseous diffusion, a liquid dopant spray-on process, and a technique where phosphorus ions are precisely driven into the surface of the silicon.

The n-type silicon doped with phosphorus cannot form an electric field by itself. One also needs p-type silicon. Boron, which has only three valence electrons, is used for doping p-type silicon (Fig. 5.3). Boron is introduced during silicon processing when the silicon is purified for use in photovoltaic devices. When a boron atom takes a position in the crystal lattice formerly occupied by a silicon atom, a bond will be missing an electron. In other words, there is an extra positively charged hole.

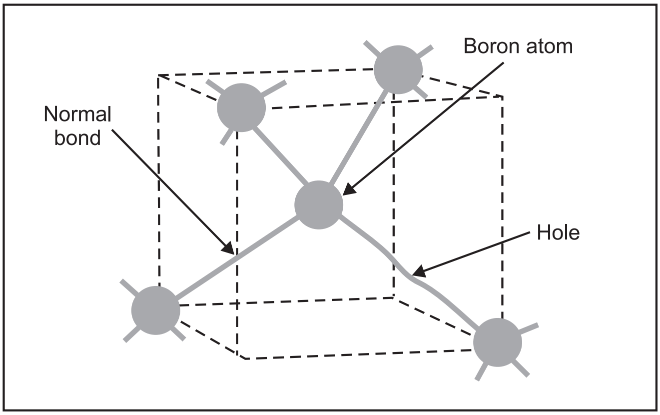



**Figure 5.3** Boron substituted p-type silicon

## 5.2.4 Absorption and conduction

In a photovoltaic cell, photons are absorbed in the p-layer. And it is very important to 'tune' this layer to the properties of incoming photons to absorb as many as possible, and thus, to free up as many electrons as possible. Another challenge is to keep the electrons from meeting up with holes and recombining with them before they can escape from the photovoltaic cell. To do all this, the material is design to free the electrons as close to the junction as possible, so that the electric field can help send the free electrons through the conduction layer (the n-layer) and out into the electrical circuit. By optimising all these characteristics, one improves the photovoltaic cell's conversion efficiency, which is how much of the light energy is converted into electrical energy by the cell.

## 5.2.5 Electrical contacts

Electrical contacts are essential to a photovoltaic cell because they bridge the connection between the semiconductor material and the external electrical load, such as a light bulb. The back contact of a cell, i.e. on the side away from the incoming sunlight, i.e. is relatively simple. It usually consists of a layer of aluminium or molybdenum metal. But the front contact, on the side facing the sun, i.e. is more complicated. When sun rays fall on the photovoltaic cell, electron current flows all over its surface. If we attach contacts only at the edges of the cell, it will not work well because of the great electrical resistance of the top semiconductor layer. Only a small number of electrons would make it to the contact.

To collect the maximum current, one must place contacts across the entire surface of a photovoltaic cell. This is normally done with a ‘grid’ of metal strips or ‘fingers’. However, placing a large grid, which is opaque, on the top of the cell shades active parts of the cell from the sun. The cell’s conversion efficiency is thus significantly reduced. To improve the conversion efficiency, we must minimise these shading effects. Another challenge in cell design is to minimise the electrical resistance losses when applying grid contacts to the solar cell material. These losses are related to the solar cell material’s property of opposing the flow of an electric current, which results in heating the material. Therefore, in designing grid contacts, we must balance shading effects against electrical resistance losses. The usual approach is to design grids with many thin, conductive fingers spreading to every part of the cell’s surface. The fingers of the grid must be thick enough to conduct well (with low resistance), but thin enough not to block much of the incoming light. This kind of grid keeps resistance losses low while shading only about 3 per cent to 5 per cent of the cell’s surface.

Grids can be expensive to make and can affect the cell’s reliability. To make top-surface grids, we can either deposit metallic vapours on a cell through a mask or paint them on via a screen-printing method. Photolithography is the preferred method for the highest quality, but has the greatest cost. This process involves transferring an image via photography, as in modern printing. An alternative to metallic grid contacts is a transparent conducting oxide (TCO) layer such as tin oxide ($SnO_2$). The advantage of TCOs is that they are nearly invisible to incoming light, and they form a good bridge from the semiconductor material to the external electrical circuit. TCOs are very useful in manufacturing processes involving a glass superstrate, which is the covering on the sun-facing side of a PV module. Some thin-film PV cells, such as amorphous silicon and cadmium telluride, use superstrates. In this process, the TCO is generally deposited as a thin film on the glass superstrate before the semiconducting layers are deposited. The semiconducting layers are then followed by a metallic contact that will actually be the bottom of the cell. The cell is actually constructed ‘upside down’, from the top to the bottom. But the construction technique is not the only thing that determines whether a metallic grid or TCO is best for a certain cell design. The sheet resistance of the semiconductor is also an important consideration. In crystalline silicon, for example, the semiconductor carries electrons well enough to reach a finger of the metallic grid. Because the metal conducts electricity better than a TCO, shading losses are less than losses associated with using a TCO. Amorphous silicon, on the other hand, conducts very poorly in the horizontal direction. Therefore, it benefits from having a TCO over its entire surface.

### 5.2.6 Antireflective coating

Since, silicon is a shiny gray material and can act as a mirror, reflecting more than 30 per cent of the light that shines on it. To improve the conversion efficiency of a solar cell, to minimise the amount of light reflected so that the semiconductor material can capture as much light as possible to use in freeing electrons. Two techniques are commonly used to reduce reflection. The first technique is to coat the top surface with a thin layer of silicon monoxide (SiO). A single layer reduces surface reflection to about 10 per cent, and a second layer can lower the reflection to less than 4 per cent. A second technique is to texture the top surface. Chemical etching creates a pattern of cones and pyramids, which capture light rays that might otherwise to deflect away from the cell. Reflected light is redirected down into the cell, where it has another chance to be absorbed.

## 5.3 Photovoltaic module performance ratings

Generally, the performances rating of photovoltaic are expressed in terms of peak watt. The peak watt (Wp) rating is determined by measuring the maximum power of a PV module under laboratory conditions of relatively high light level, favourable air mass, and low cell temperature. But these conditions are not typical in the real world. Therefore, one may uses a different procedure, known as the normal operating cell temperature (NOCT) rating. In this procedure, the module first equilibrates with a specified ambient temperature so that maximum power is measured at a nominal operating cell temperature. This NOCT rating results in a lower watt value than the peak-watt rating, but it is probably more realistic. Neither of these methods is designed to indicate the performance of a solar module under realistic operating conditions. Another technique, the AMPM Standard, involves considering the whole day rather than 'peak' sunshine hours. This standard, which seeks to address the practical user's needs, is based on the description of a standard solar global-average day (or a practical global average) in terms of light levels, ambient temperature, and air mass. Solar arrays are designed to provide specified amounts of electricity under certain conditions. The following factors are usually considered when determining array performance: characterisation of solar cell electrical performance, determination of degradation factors related to array design and assembly, conversion of environmental considerations into solar cell operating temperatures, and calculation of array power output capability.

### 5.3.1 Power output

Power available at the power regulator, specified either as peak power or average power produced during one day.

### 5.3.2 Energy output

The energy is expressed as watt-hour or Wh. This indicates the amount of energy produced during a certain period of time. The parameters are output per unit of array area ($Wh/m^2$), output per unit of array mass (Wh/kg), and output per unit of array cost (Wh/$).

### 5.3.3 Conversion efficiency

This parameter is defined as:

$$\frac{\text{Energy output from array}}{\text{Energy input from sun}} \times 100$$

This last parameter is often given as a power efficiency, equal to 'power output from array'/'power input from sun' × 100 per cent. Power is typically given in units of watts (W), and energy is typical in units of watt-hours (Wh). To ensure the consistency and quality of photovoltaic systems and increase consumer confidence in system performance, various groups such as the Institute of Electrical and Electronics Engineers (IEEE) and the American Society for Testing and Materials (ASTM) are working on standards and performance criteria for photovoltaic systems.

## 5.4 Reliability of photovoltaic systems

Reliability of photovoltaic arrays is an important factor in the cost of systems and in consumers accepting this technology. The photovoltaic cell itself is considered a 'solid-state' device with no moving parts, and therefore, it is highly reliable and long-lived. Therefore, reliability of photovoltaic usually focuses not on cells, but on modules and systems. One way to measure reliability is the rate of failure of particular parts. The failure of solar cells mostly involves cell cracking, interconnect failures (resulting in open circuits or short circuits), and increased contact resistance. Module-level failures include glass breakage, electrical insulation breakdown, and various types of encapsulate failures.

Fault-tolerant circuit design involves using various redundant features in the circuit to control the effect of partial failure on overall module yield and array power degradation. Degradation can be controlled by dividing the modules into a number of parallel solar cell networks called branch circuits. This type of design can also improve module losses due to broken cells and other circuit failures. Bypass diodes or other corrective measures can mitigate the effects of local cell hot-spots. Replacement of the entire module is a final option in dealing with photovoltaic array failures. However, today's component failure rates are low enough that, with multiple-cell interconnects, series/paralleling, and bypass diodes; it is possible to achieve high levels of reliability.

## 5.5 Classification of photovoltaic systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principle classifications are grid-connected or utility-interactive systems and stand-alone systems. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

### 5.5.1 Grid-connected (utility-interactive) PV systems

Grid-connected or utility-interactive photovoltaic systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component in grid-connected photovoltaic systems is the inverter or power conditioning unit (PCU). The PCU converts the DC power produced by the photovoltaic array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energised (Fig. 5.4). A bi-directional interface is made between the photovoltaic system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the photovoltaic system to either supply on-site electrical loads or to back feed the grid when the photovoltaic system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the photovoltaic system output, the balance of power required by the loads is received from the electric utility This safety feature is required in all grid-connected photovoltaic systems, and ensures that the photovoltaic system will not continue to operate and feed back onto the utility grid when the grid is down for service or repair.

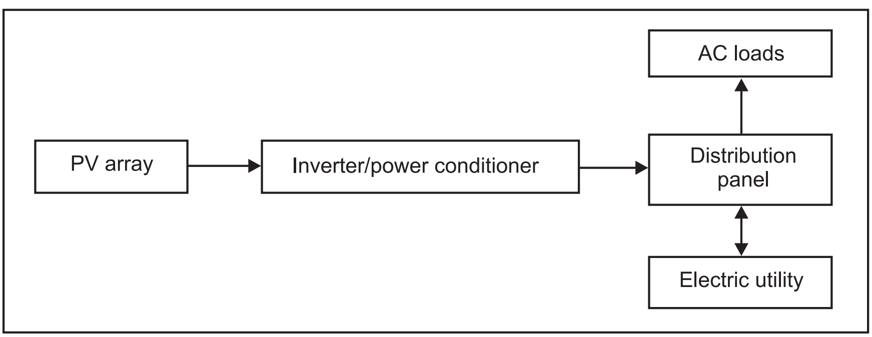



**Figure 5.4** Diagram of grid-connected photovoltaic system

### 5.5.2 Stand-alone photovoltaic systems

Stand-alone photovoltaic systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a photovoltaic array only or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a photovoltaic-hybrid system. The simplest type of stand-alone photovoltaic system is a direct-coupled system, where the DC output of a photovoltaic module or array is directly connected to a DC load (Fig. 5.5). Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the photovoltaic array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps; a type of electronic DC–DC converter, called a maximum power point tracker (MPPT) is used between the array and load to help better utilise the available array maximum power output.

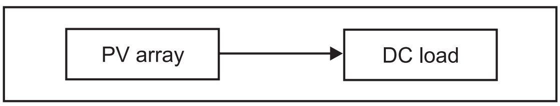



**Figure 5.5** Simplest type of stand-alone PV system

In many stand-alone photovoltaic systems, batteries are used for energy storage. Figure 5.6 shows a diagram of a typical stand-alone PV system powering DC and AC loads. Figure 5.7 shows how a typical photovoltaic hybrid system might be configured.

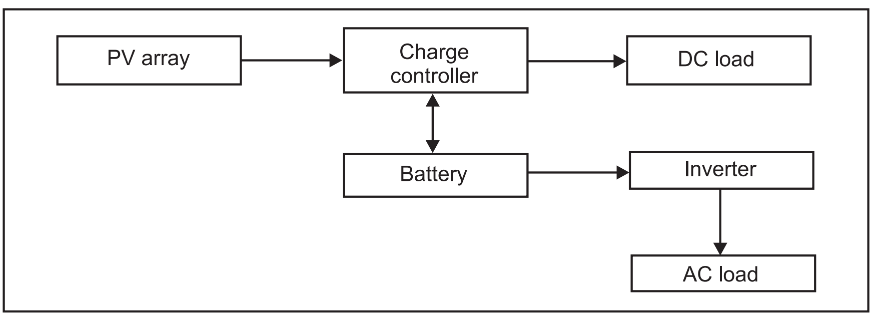



**Figure 5.6** Diagram of stand-alone PV system with battery storage powering DC and AC loads

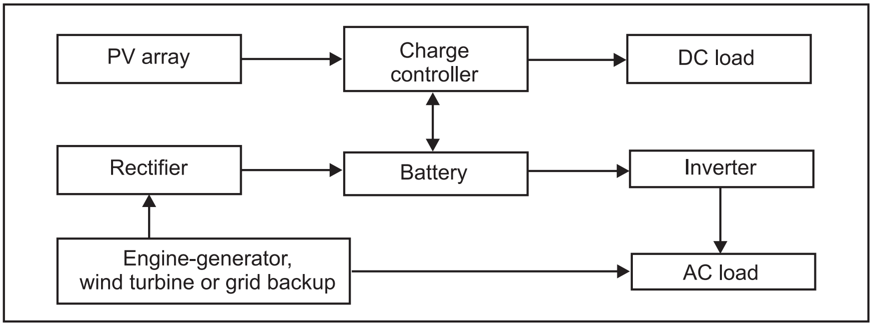



**Figure 5.7** Diagram of photovoltaic hybrid system

## 5.6 Non-silicon-based photovoltaic systems

The alternative material and technology used in manufacturing photovoltaic components, termed as second and third generation photovoltaic technologies include less-costly raw material and manufacturing techniques. Second generation photovoltaic imply thin-film solar cells, that use amorphous silicon or other compounds with semi-conducting properties, which are deposited on flexible substrates ranging from glass to plastics and other polymers. Third generation technologies include organic, nano and spheral technologies. Most of these are presently in the process of development and are soon expected to be commercially produced.

### 5.6.1 Thin-film technology

Thin-film silicon solar cells offset many of the disadvantages of the conventional silicon cells by using a fraction of the pure silicon required in manufacturing solar cells. They are also easier to manufacture and easy to use in a variety of applications.

Thin-film solar cells are made by depositing a thin layer of semiconductor on a supporting material (substrates) such as glass, stainless steel or polyimide through a process called chemical vapour deposition. The materials selected for deposition are strong light absorbers, most commonly amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium (gallium) diselenide (CIS or CIGS). These materials are suitable for deposition over large substrate areas (up to 1 metre) and hence allow high volume manufacturing. In terms of costs, amorphous silicon thin film solar cells use less than 1 per cent of the silicon used in conventional cells, and the material costs are also lower for cells using CdTe or CIS technologies. These cells also do not require assembling and are flexible, hence having versatile applications. The efficiency levels of these cells range between 6 to 8 per cent.

### 5.6.2 Amorphous silicon (a-Si)

Used mostly in consumer electronic products, which require lower power output and cost of production, amorphous silicon has been the dominant thin-film PV material since it was first discovered in 1974. Amorphous silicon is a non-crystalline form of silicon, i.e. its silicon atoms are disordered in structure. A significant advantage of a-Si is its high light absorptivity, about 40 times higher than that of single-crystal silicon. Therefore only a thin layer of a-Si is sufficient for making PV cells (about 1 micrometre thick as compared to 200 or more micrometres thick for crystalline silicon cells). Also, a-Si can be deposited on various low-cost substrates, including steel, glass and plastic, and the manufacturing process requires lower temperatures and thus less energy. So the total material costs and manufacturing costs are lower per unit area as compared to those of crystalline silicon cells.

Despite the promising economic advantages, a-Si still has two major roadblocks to overcome. One is the low cell energy conversion efficiency, ranging between 59 per cent, and the other is the outdoor reliability problem in which the efficiency degrades within a few months of exposure to sunlight, losing about 10–15 per cent.

### 5.6.3 Cadmium telluride (CdTe)

As a polycrystalline semiconductor compound made of cadmium and tellurium, CdTe has a high light absorptivity level; only about a micrometre thick can absorb 90 per cent of the solar spectrum. Another advantage is that it is relatively easy and cheap to manufacture by processes such as high-rate evaporation, spraying or screen printing. The conversion efficiency for a CdTe commercial module is about 7 per cent, similar to that of a-Si. The instability of cell and module performance is one of the major drawbacks of using CdTe for PV cells. Another disadvantage is that cadmium is a toxic substance. Although very little cadmium is used in CdTe modules, extra precautions have to be taken in manufacturing process.

### 5.6.4 Copper indium diselenide ($CuInSe_2$ or CIS)

A polycrystalline semiconductor compound of copper, indium and selenium, CIS has been one of the major research areas in the thin-film industry. The reason for it to receive so much attention is that CIS has the highest 'research' energy conversion efficiency of 19.7 per cent in 2006 is not only the best among all the existing thin-film materials, but also came close to the 18 per cent research efficiency of the polycrystalline silicon PV cells. (A prototype CIS power module has a conversion efficiency of 10 per cent.) Being able to deliver such high energy conversion efficiency without suffering from the outdoor degradation problem, CIS has demonstrated that thin-film PV cells are a viable and competitive choice for the solar industry in the future.

CIS is also one of the most light-absorbent semiconductors; 0.5 micrometres can absorb 90 per cent of the solar spectrum. CIS is an efficient but complex material. Its complexity makes it difficult to manufacture. Also, safety issues might be another concern in the manufacturing process as it involves hydrogen selenide, an extremely toxic gas. So far, CIS is not commercially available yet although Siemens solar has plans to commercialise CIS thin-film PV modules.

### 5.6.5 Nanotechnology in photovoltaic

Various nanosize materials are under investigation; the major advantage of nanoparticle in the field of photovoltaics is increases in the charge transfer rate and tunability, which can be achieved by reducing the particle size. By controlling the particle size one can tune the band gap of the material so that it matches well with the solar spectrum and render the nanoparticles ideal for photovoltaic applications. Various attempts have been under investigation and it is believed that the appropriate photovoltaic system with maximum efficiency will be achieved in sooner.

### 5.6.6 Organic technology

Organic solar cells are based on the photosynthesis process in plants. The absorption of light in organic cells is done by the ‘dye’ which substitutes for the silicon in conventional cells. This light causes the dye molecules to excite and release electrons that are converted to electrical energy. The use of chemicals called dyes for the conversion process has led to organic cells also being known as ‘dye-sensitised solar cells’. The absorption of light occurs in dye molecules that are in a highly porous film of titanium dioxide ($TiO_2$). This causes the electron to be injected into $TiO_2$ and is conducted to the transparent conductive oxide layer. The material and manufacturing costs of these cells are relatively much lower than conventional silicon photovoltaic cells. However, the low efficiency rates (3–5 per cent) result in an overall increase in the costs. This technology is presently being developed and expected to be produced commercially.

## 5.7 Asphalt roads as solar power producers

Researchers at the University of Rhode Island are starting research into using the miles and miles of roads that stretch across our country as solar power producers. It is a well-known phenomenon that roads collect a lot of heat from sunlight during the day. This heat collection is so extreme that it is blamed for the increased heat that is associated with urban centres as compared to areas with fewer roads. The researchers are exploring four ways to collect and harness that energy. The most basic approach is to attach photovoltaic cells to all the exposed areas of the roads. The flexible cells could be attached to the barriers on the roads and embedded in the roadway in areas like the shoulders where vehicles typically do not travel. The electricity produced could be collected and used locally to power street lights and signs. The great thing about current flexible PV cells is that they do not have to be pointed directly at the sun, so they could be placed anywhere where there is sunlight and still collect power during the day.

A second intriguing idea is embedding water filled piping into the road bed that would collect heat from the sun. As the water warms it would circulate into areas where ice and snow accumulate thus melting the snow and ice and reducing the need for salt to be used on the roads. The warm water could also be circulated to nearby buildings to assist in the heating needs of the structures as well as for hot water. This system would be very similar to the geothermal heat pumps which are already in use in many homes and buildings around the country, producing heating and hot water at minimal cost. And, of course, the heat could be used as steam to turn a steam turbine and produce electricity as well.

The third idea works on the thermal-electric principal that a small electric current is produced when a hot and cold location are connected using two types of semi-conductors. By putting semi-conductors in different places in the roadway, like in the sunny and the shady areas, a current could be produced. Although there are no practical applications of this idea yet, research suggests it could produce enough electricity to de-ice roads.

# 6

# Energy consuming and converting equipments

## 6.1 Introduction

Energy is available in various forms in nature. Normally energy is utilised in a form different from the one in which it is available. We therefore require equipments which convert energy from one form to a more conveniently usable form. Broadly we can categorise the equipment as: (i) energy-converting equipment, and (ii) energy-using or -consuming equipment.

There is however a thin demarcation line between the two. In fact the energy-consuming equipments are also converting the energy into some from of useful activity to carry out a particular assignment. Under energy-converting equipment, we can identify the following major equipments and systems: (i) boilers, (ii) turbines (hydro steam, gas and nuclear), (iii) generators, (iv) batteries, (v) solar cells/fuel cells, and (vi) nuclear reactors.

Under energy-consuming equipments, we can identify the following equipments: (i) motor, (ii) fans, (iii) pumps, (iv) crushers/grinders, (v) heaters, and (vi) misc. appliances.

## 6.2 Boilers

The steam generator or boiler is a combination of systems and equipments for the purpose of converting chemical energy from fossil fuels into thermal energy and transferring the resulting thermal energy to a working fluid, usually water, for use in high-temperature processes or for partial conversion to mechanical energy in a turbine. In most modern large power plants, one boiler is used to supply steam to one steam-turbine generator unit. The boiler complex includes the air-handling equipment and ductwork, the fuel-handling system, the water-supply system, the steam drums and piping, the exhaust-gas system, and the pollution-control system.

Steam generators are the most common vaporisers. They fall into two general categories, namely, (i) industrial; and (ii) power-utility steam boilers.

Industrial steam boiler types include fire-tube boilers and waste-tube boilers. Fire-tube boilers (or steam generators) are characterised by the containment of the products of combustion within the tubes of the boiler. The water being vaporised surrounds the tubes and is contained by a larger shell with front and rear tube sheets. Almost all fire-tube boilers built today are of the modified Scotch marine type. This design utilises a central cylindrical combustion chamber with return of the gases through smaller tubes. Baffles are frequently provided to return the gases through more tubes for a third or fourth pass. These units are usually completed as a shop-erected package boiler with all combustion equipment and controls installed and ready to operate after electrical and piping connections are made at the place of utilisation. Fire-tube boilers are rated for capacity in terms of boiler horsepower. One boiler horsepower is defined as the ability to evaporate 34.5 lb water from and at 212°F. Such units are available in size from 5 to 600 hp (about 20,000 lb/hr steam) and in pressures to 250 lb/sq. inch. For the size and pressure range they are very competitive in price and installation costs. They do not lend themselves readily to the installation of superheaters and are thus limited to the generation of saturated steam only. They are applicable to oil and gas-fuel firing only.

Water-tube boilers are characterised by the containment of the vaporising water within the tubes while the products of combustion are on the outer surfaces. The furnace chamber may consist of containment by either refractory walls or special configurations of the water tubes. For economic reasons, size of 10,000 to 1,20,000 lb/hr are generally of 'package' shop-erected construction. These are currently available only for oil and gas-fuel firing, with active work underway to develop similar coal-fired units. A few coal-fired units have been built but full acceptance and utilisation have yet to develop. Larger-capacity oil and gas-fired units and almost all coal-fired units are generally 'field-erected' or constructed in place. Since the water tubes are of small diameter compared with the shells of fire-tube boilers, there is no similar limitation on their operating pressures.

Many older water-tube boilers are of the straight-water-tube construction, but modern units are almost universally of bent water-tube design. The use of bent tubes allows extreme flexibility in design. The shaping of the tubes to enclose the combustion space has sharply reduced the amount of refractory used and has permitted higher rates of burning within the combustion space. Superheaters may be readily fitted to such units. Industrial units in excess of 2,50,000 lb/hr capacity are rare and operating pressures in excess of 600 lb/sq. inch are also seldom encountered. Higher-pressure units are sometimes installed where electric power is generated within the plant, but the economic trends had been away from power generation with a few notable exceptions.

Utility boilers include conventional boilers and unconventional boilers. Conventional boilers used in power utility plants are those units operating below the critical pressure of the steam with widely accepted modes of operation. They may include features that yesterday were unconventional such as forced circulation, reheat, divided furnaces, once-through flow, and pressurised furnaces. They are usually custom-designed and built, with the trend to larger units in the multi-million pounds per hour capacity. Their superheated output is taken directly to a single turbine generator in recent designs for the production of electricity. They are universally of water-tube design, and all fuels are fired, with coal being the most common.

Unconventional boilers are those which are experimental or extremely rare in their application. Currently, mercury binary, combination gas turbine, supercritical, and nuclear boilers are in this category. Supercritical units are conventionally fired once-through forced-fluid-flow designs where the entire system is pressurised over the critical vapour pressure. Units of over 5000 lb/sq. inch operating pressure have been constructed and are in operation. Mercury-binary-system boilers impose a mercury-vapour topping system on a conventional steam cycle. The mercury is vaporised at a high saturated vapour temperature by conventional fuel firing. After electricity is produced in a mercury-vapour turbine generator the latent heat of the mercury is transferred to steam in a condenser-boiler. A number of such plants have been built and are in operation. Combination gas-turbine and steam-turbine plants have been built for many years (Velox boilers). New designs are currently being built which incorporate a more active part by the gas turbine. These designs include those where the exhaust gases of large gas turbines are re-heated by supplemental fuel firing to serve as the combustion gases of conventional steam boilers. Nuclear units have been built for power utility steam boilers in the United States and other parts of the world. It does not appear that they will compete economically with fossil-fuel plants until fundamental problems in fuel preparation and waste disposal are solved.

## 6.3 Turbines

A turbine is a device that converts the stored mechanical energy in a fluid into rotational mechanical energy. There are several different types of turbines, including steam turbines, gas turbines, water turbines and wind turbines or wind mills. The material presented in this section is applicable to only steam and gas turbines.

### 6.3.1 Steam turbines

'A steam turbine may be defined as a form of heat engine in which the energy of the steam is transformed into kinetic energy by means of expansion through nozzles, and the kinetic energy of the resulting jet is in turn converted into force doing work on rings of blading mounted on a rotating part.'

This definition may be restated as ‘A steam turbine is a prime mover which converts the thermal energy of steam directly into mechanical energy of rotation.’

The gas turbine is an internal combustion engine differing in many respects from the standard reciprocating model. In the first place, the process by which a gas turbine operates involves steady flow; hence pistons and cylinders are eliminated. Secondly, each part of the thermodynamic cycle is carried out in a separate apparatus. The basic process involves compression of air in a compressor, introduction of the compressed air and fuel into the combustion chamber(s), and finally expansion of the gaseous combustion products in a power turbine.

A steam turbine is probably the most flexible driver available to industry. With the advent of modern precision gears, turbine speeds are seldom below 1200 rpm and may be as high as 25,000 rpm. Radial-flow units operating at still higher speeds (50,000 rpm) have been used in the refrigeration of process gases. Most designs are for a single speed either to drive electric generators or to operate over a limited speed range for industrial applications. Turbines developing full torque at reduced speeds may require special design considerations. Marine turbines are built with reversing stages to go from ahead to reverse rotation. Turbines can utilise steam at very low pressures or as high as 5000 lb/sq. inch. The exhaust can be any pressure lower than the inlet that will economically develop power, and in modern power plants this is frequently as low as 1 inch Hg absolute. Turbines can be used as pressure-reducing stations, taking steam at one level and exhausting it at a lower-pressure level, thus developing power and reducing steam temperature. In modernising old utility plants, a new high-pressure boiler and a ‘topping turbine’ can provide additional power and furnish steam to the original turbines with increased overall plant efficiency.

Design characteristics; sizes are based on shaft power, in terms of horsepower for mechanical-drive turbines, and in kilowatts for turboelectric generators. Frame size depends on the number and types of stages, blade lengths, and wheel diameters. Physical size alone does not indicate the power rating, since the power output of a frame is proportional to steam-pressure level.

Turbines are built in power outputs from fractional horsepower up to 5,00,000 kW. In the larger sizes, a turbine may consist of several different casings in series, i.e. a high-pressure turbine, an intermediate-pressure turbine, and a single or double-flow low-pressure turbine. Regardless of the number of casings, an installation is considered a single turbine as long as it is controlled by a single governor. Each unit of the turbine may have its own overspeed trips or special safety devices including those used for reheat installations.

Process plant drivers are seldom large enough or use a high enough steam pressure to justify more than one turbine casing. The following types of turbines are commonly used in process industries:

1. Straight-through turbines have only one inlet and one exhaust steam connection, either single or multi-stage.
2. Bleeder turbines are multi-stage turbines with outlets at one or more of the stages, so that steam may be bled and used for boiler feed water heating or process requirements.
3. Extraction turbines are bleeder turbines with the bleed pressure controlled and thus they constitute essentially two or more turbines in a single casing.
4. Mixed-pressure turbines have a governor admitting steam to the low-pressure end of a turbine and another governor admitting enough high-pressure steam to the high-pressure end to carry the load.
5. An extraction-induction turbine, is a combination mixed-pressure-extraction turbine, in that it can either supply or use low-pressure steam.

In all these casing arrangements the turbines may be condensing (exhausting to a condenser) or back-pressure exhausting to process or other uses.

## *Selection*

Since all turbines have essentially the same operating characteristics, the user should be concerned primarily with guaranteed efficiencies, operating conditions and performance curves. Comparison of efficiencies and performance must, of course, be on an equivalent basis. Some manufacturers guarantee that turbine performance will be equal to or greater than the quoted value. Others allow a plus or minus variation. At part loads, reaction blades, because of their greater ability to utilise 'carry-over', may show better efficiencies.

Turbines for electric power generation are designed for operation at only one speed and under standard steam conditions. Process drives, usually known as mechanical-drive turbines, have to meet a wide variety of speed and steam conditions, and about the only standardisation that can be effected is in blading and casing patterns. The casings are usually selected from a series of high-pressure ends, intermediate spool pieces, and exhaust ends that can be bolted together in a variety of combinations.

The most frequently used steam turbine is the single-stage mechanical-drive turbine, which is low in cost and is made in several frame sizes, from 9- up to 24-inch wheels. Cast-iron casings are used for low steam temperatures and pressures and cast steel for the higher pressures and temperatures. A minimum of one nozzle can be used in each size, but the maximum nozzle area that can be installed increases rapidly with increased frame size.

The power that a turbine can develop is a function of size, steam conditions, and rpm. The lowest investment cost results from the use of the smallest possible turbine. For most applications, however, the additional investment in larger turbines will be paid for in a short time by reduced steam consumption.

The general-purpose turbines can usually operate from zero speed to full speed at any torque requirement within the temperature limits of the casing. The speed governors are of the simple direct-acting type, with at least a hand speed changer, although some models may include provisions for either pneumatic or electrically actuated speed reset.

### *Operation and safety consideration*

By adjusting the throttling or governing valve the quantity of steam flow can be varied from zero to full flow. For each flow the turbine will have definite speed-torque characteristics, and a turbine will speed up until its torque is equal to that required by the driven equipment. If greater torque and speed are required the governor opening is increased to give more steam flow. Most turbines will burst at their 'runaway' speed, and as a result the user seldom changes the governing valve directly. The preferred procedure is to reset the speed setting of the governor and let it change the valve.

Turbines without governing valves are used under special situations. For example, where (i) the speed of a turbocharger turbine depends on the gas flow through an engine (i.e., engine rpm) and failure of the supercharging compressor will cause the engine to shut-down; (ii) turbines driving the lubrication-oil pumps of a larger turbine are frequently designed for 'runaway' speeds; and (iii) gas-turbine governors vary fuel rate and hence the speed.

Turbines can be installed with the necessary supervisory instrumentation to start up automatically and to shut-down in the event of malfunction of failures. Failure of lubricating oil automatically shuts the trip throttle valve. In addition, trips can be connected to vibration-detecting devices and temperature detectors in the inlet and exhaust piping.

A turbine has maximum available torque at zero speed and therefore the load does not have to be disconnected during start-up. The preferred starting procedure is to warm up the lubricating oil system by first placing it in operation. Then the turbine should be warmed up gradually by opening the throttle valve to bring the speed up slowly as the turbine warms up. This procedure minimises the possibility of turbine 'rubs'. Some of the smaller multi-stage turbines used as process drives can be started quickly when occasion demands it. The shut-down procedure of large turbines is critical and the rotors are turned slowly while the casing cools to prevent hot spots that might cause ‘kinking’ of the shaft.

A turbine can operate satisfactorily with the moisture that forms naturally in the stages, provided the casing is drained to prevent accumulation. The inlet-steam piping should be designed to provide dry steam to the turbine nozzle since a slug of moisture can knock out blades and/or thrust bearings.

Solids carried over from the boiler drum are deposited principally in turbine nozzles, resulting in lower turbine output. Their presence can be detected by higher than normal interstage pressures. These deposited principally in turbine nozzles, resulting in lower turbine output. These deposits can be washed out by injecting water into the turbine while it is running, but under conditions prescribed by the manufacturer to prevent turbine damage.

It is good practice to inspect turbines periodically, but the interval between shut-downs for thorough inspection is longer than those for other plant elements. Annual boiler inspections or the cleaning of heat exchangers in a chemical plant are often appropriate occasions. A steam turbine is generally considered to have 100 per cent availability, with longer than a year between shut-downs, provided its performance is periodically checked.

Most important is the checking of the safety features that have been incorporated to protect the turbine. For example, the operation of overspeed trips can be checked by using these to shut-down the turbine. Many continuous process drivers cannot be shut-down, and these safety features can only be checked during plant turnarounds. The only preventive maintenance required is to (i) keep the oil clean, at the correct temperature, and at the right level in the oil reservoir, (ii) inspect and check auxiliaries such as lubricating-oil pumps, coolers, and oil strainers, (iii) inspect turbine parts during the annual turnaround, and (iv) check safety devices.

## *Heat recovery*

Since two-third of the heat entering the turbine leaves in the steam exhaust, with other losses minor, the major improvement in thermal efficiency results from the use of exhaust and/or extraction steam for heating, process or other purposes. The smallest amount of steam that can be used for heating purposes is that required for heating boiler feed water.

Turbine steam consumption can be decreased by superheating. The energy available (Btu/lb) for given inlet and exhaust pressure is proportional to the absolute inlet steam temperature. Frequently economics justify the addition of superheaters to waste-heat boiler installations.

Turbines that operate over a wide load change should have first-stage nozzle area control. Economics do not ordinarily justify controlling the nozzle areas of the other stages, except for extraction or mixed-pressure turbines where nozzle area control of the first stage in the low-pressure parts can be used. Nozzle area can be changed by hand valves or automatically by the governor.

Turbines that run at constant speed but at zero load for considerable periods will require less steam at this condition if the casing is under vacuum or if the speed is reduced. Under a vacuum and zero load, 5–10 per cent of full-load steam flow is required. Turbines that run at one load and at overloads for only short periods should be designed to carry overloads with an overload valve.

## *Combustion of gas turbines*

Gas turbines are usually rated according to power output at sea level and 80°F ambient air (some European designs are rated at 60°F) and when burning a specified fuel. Power output and efficiency will be larger for those fuels which produce larger volumes of products of combustion since the compressor does not do any work on additional volume. Gas turbines are further classified by the physical arrangements of the component parts, such as (i) single shaft, (ii) two shaft, (iii) regenerative (a heat exchanger is used to recover exhaust losses and heat the air to the combustors), (iv) intercooled (heat removed between compressors), and (v) reheat (heat added between turbines).

The overall efficiency of a gas turbine is a function of compressor and turbine efficiencies, ambient air temperature, nozzle inlet temperature, and type of cycle used (i.e. reheat, etc.). The compressor and turbine are designed for high efficiency and the first-stage gas temperature establishes material and stress conditions for the first set of rotating blades. To the gas temperature at these blades is added the temperature drop across the first-stage nozzles to determine the inlet temperature of the turbine, which may vary from 1300° to 1500°F for industrial gas turbines and higher for aviation gas turbines. The higher values are usually used in impulse turbines.

In a simple cycle turbine, there is, for each turbine inlet temperature, an optimum pressure ratio producing the highest possible efficiency. The efficiency and optimum pressure ratio increases with increasing turbine inlet temperatures. These pressure ratios vary from 4 at 1300°F up to 6 for 1500°F turbine inlet temperature.

Regenerative cycles favour lower pressure ratios which results in low compressor discharge temperatures, thus allowing greater recovery, of heat from the turbine exhaust gases. High-ratio regenerative plants use intercoolers in the compressor circuit to lower the compressor discharge air temperature.

### *Turbine pumps*

The term turbine pump is applied to units with mixed-flow (i.e. part axial and part centrifugal) impellers. Such units are available in capacities starting 100 gal/min upward for heads up to about 100 ft per stage. Turbine pumps are usually vertical.

A common form of turbine pump has the pump element mounted at the bottom of a column that serves as the discharge pipe. Such units are immersed in the liquid to be pumped and are commonly used for wells, condenser circulating water, large volume drainage, etc. Another form of the pump has a shell surrounding the pumping element which is connected to the intake pipe. In this form the pump is used on condensate service in power plants and for process work in oil refineries and elsewhere.

Regenerative pumps, also sometimes referred to as turbine pumps because of the shape of the impeller, employ a combination of mechanical impulse and centrifugal force to produce heads of several hundred feet at low volumes (usually less than 100 gal/min). The impeller, which rotates at high speed with small clearances, has many short radial passages milled on each side at the periphery. Similar channels are milled in the mating surfaces of the casing. Upon entering, the liquid is directed into the impeller passages and proceeds in a spiral pattern around the periphery, passing alternately from impeller to the casing, receiving successive impulses as it does so.

These pumps are particularly useful where it is required to handle low volumes of low-viscosity liquids at higher pressures than are normally available with centrifugal pumps. Close clearances limit their use to clean liquids. For very high heads multiple-stage units are available.

## 6.4 Diesel generating sets (DG sets)

Many industries operate DG sets on continuous basis for various reasons like economy, reliability of power, etc. Many industries have processes which emits lots of energy to atmosphere. One must be aware that huge amount of heat energy is rejected to the atmosphere through exhaust gases and jacket cooling system (the heat energy rejected to atmosphere is to the tune of 60 to 67 per cent of input energy from the fuel burnt in the engine generator set). Process like incineration, sulphonation, cement plant kilns, glass furnaces, steel plant furnaces emit huge amount of heat energy to atmosphere.

This waste heat can be converted into useful forms like:

1. Steam
2. Hot oil
3. Hot air

4. Hot water
5. Chilling
6. Refrigeration
7. Electricity
8. Waste-water recycling

The fuel cost of DG sets is a substantial part of running cost for all process industries. The prices of petroleum fuels in India have increased considerably. This has substantially increased the running cost of these DG sets.

Waste heat recovery system on existing resources in this era of 'self-reliance' is essential when our import bill of petroleum products is scaling to new heights. It is not only in individual company's interest, but also in national interest, that, by recovering the waste heat we reduce our fuel import bill.

This section highlights on waste heat recovery from furnace oil/gas fired DG sets, process and furnace with its heat recovery units.

Few salient features of exhaust heat recovery systems are listed below:

1. Payback period varies in the range of 6 months to 18 months.
2. Waste heat recovery boiler (WHRB) can be provided with economiser/ feed water preheated to improve the performance.
3. The equipment can be designed within the back pressure constraints of primary equipment and does not affect the performance of source equipment in any way if designed properly.
4. Variety of designs is possible to suit different types of exhaust gases.
   (a) Smoke tube type
   (b) Water tube type (bare tube/finned tube construction)
5. Suitable for wide range of temperature and pressures.
6. Waste heat recovery systems can be provided with isolation and bypass facility on gas side by fully automatic three-way pneumatically operated diverter valve.
7. Particulate deposited from dirty gases can be removed with on-line soot blowing valve.
8. Location of heat recovery boiler can be indoor as well as outdoor. Following safety instruments are provided for safe and reliable operation of WHRB as well as engine genset.
   (a) High steam pressure.
   (b) High exhaust back pressure.
   (c) Low water level in boiler.
9. Economiser/feed water pre-heater for WHRB can be provided with unique control circuit for operation against cold end corrosion due to sulphur in fuel (only applicable for heavy oil fired engine genset).

## 6.5 Motors

Electric motors are the prime movers of any industry. Electric motor efficiency is the measure of its ability to convert kilowatt of electric power supplied to the motor terminal and the horsepower of mechanical energy taken out of the motor at the rotating shaft.

Conservation of electrical energy is one of the prime requirements of today and future times. Due to drastic increase in electricity tariff, use of energy efficient motors for all the applications is inevitable. Indian industry/OEMs normally look at initial costs rather than running cost, leading to purchase of standard motors with low efficiency at full load/at partial loads. During life of motors, they are rewound ineffectively leading to further reduction of efficiency and leading to consumption of more power. The gap between power generated and demand is widening. Due to the above reasons now it is a 'National Priority', since 70 per cent of the energy consumed is used for driving electric motors. There exists a national BIS standard for three phase EE induction motors up to 37 kW. Energy efficient motors are about 15 per cent more expensive. With this increase in price the payback period is only about 1 year for 1500 working hours per annum.

Although induction motors require a minimum of attention in service, they should be inspected at regular intervals to check for excessive: (i) dirt, (ii) moisture, (iii) friction, and (iv) vibration, which account for 90 per cent of all motor failures.

There are two basic types of bearings used in integral horsepower induction motors, sleeve bearings and ball bearings. For modern motors, ball bearings are more popular. With proper design, application, and maintenance, each type will give good service.

Any of the following drive methods may be used, depending on the particular motors application: (i) V-belts drive, (ii) chain drive, (iii) gear drive, and (iv) direct drive.

Be sure the motor is connected as shown on the name-plate diagram, and that the power supply (voltage, frequency, and number of phases) corresponds with the nameplate data.

Run the motor without load to check the connections and direction of rotation. The motor will operate satisfactorily with a 10 per cent variation in voltage, a 5 per cent variation in frequency or a combined voltage and frequency variation of 10 per cent, but not necessarily in accordance with the standards of performance established for operation at normal rating.

### *Features of energy efficient motor*

1. Highest efficiency
2. Lower operating cost

3. Lower demand charges
4. Has higher overload capacity
5. Suitable for operations at higher ambient temperature
6. Fewer power factor correction
7. Lower branch circuit losses
8. Reduced air-conditioned load
9. Saving increases with time
10. Confirmation with NEMA standards of protection and control
11. Cooler and quieter operation
12. Longer insulation life: EEM windings run about 20°C cooler which increases insulation life by four times
13. Improved bearing life: EEM bearings run about 10°C cooler than standard motor (STM) bearings, which doubles the life
14. Less starting thermal stress
15. Higher service factors
16. Better suited for energy management systems
17. EEM performs better under adverse conditions of abnormal voltage conditions like unbalanced voltages.
18. Efficiency of EEM remains almost constant from 50 to 100 per cent of load.

## 6.6 Pumps

Necessity for the movement of liquids by pumping occurs often throughout a manufacturing plant. Raw materials may be delivered to the plant as liquids. Many materials are liquids during all or part of the manufacturing processes. Water and sanitary services may require pumps as do steam-generating equipments, cooling and washing equipments, etc.

Pumps may be classified on the basis of the applications they serve, the materials from which they are constructed, the liquids they handle, and even their orientation in space. All such classifications, however, are limited in scope and tend to substantially overlap each other. A more basic system of classification, the one used, first defines the principle by which energy is added to the fluid, goes on to identify the means by which this principle is implemented, and finally delineates specific geometries commonly employed. This system is therefore related to the pump itself and is unrelated to any consideration external to the pump or even to the materials from which it may be constructed.

Under this system, all pumps may be divided into two major categories: (i) dynamic, in which energy is continuously added to increase the fluid velocities within the machine to values in excess of those occurring at the discharge such that subsequent velocity reduction within or beyond the pump produces a pressure increase; and (ii) displacement, in which energy is periodically added by application of force to one or more movable boundaries of any desired number of enclosed, fluid-containing volumes, resulting in a direct increase in pressure up to the value required to move the fluid through valves or ports into the discharge line. Dynamic pumps may be further subdivided into several varieties of centrifugal and other special-effect pumps. Displacement pumps are essentially divided into reciprocating and rotary types, depending on the nature of movement of the pressure-producing members.

Energy savings in pumping systems account for 40 per cent power in the industrial sector and 15 per cent of the national consumption of India.

Centrifugal pump consists of a set of rotating vanes, enclosed within a housing or casing and used to impart energy to a fluid through centrifugal force. Thus, stripped of all refinements, a centrifugal pump has two main parts: (i) a rotating element, including an impeller and a shaft; and (ii) a stationary element made up of a casing, stuffing box, and bearings.

In a centrifugal pump the liquid is forced, by atmospheric or other pressure, into a set of rotating vanes. These vanes constitute an impeller which discharges the liquid at its periphery at a higher velocity. This velocity is converted to pressure energy by means of a volute or by a set of stationary diffusion vanes surrounding the impeller periphery. Pumps with volute casings are generally called volute pumps, while those with diffusion vanes are called diffuser pumps. Diffuser pumps were once quite commonly called turbine pumps, but this term has recently been more selectively applied to the vertical deep-well centrifugal diffuser pumps usually referred to as vertical turbine pumps.

Centrifugal pump is selected on the basis of discharge requirements and total head of the system. While selecting operating speed, there are certain limitations from site conditions like available NPSH or available submergence, etc. It is recommended that the speed should be so selected that pump has maximum achievable efficiency. As per hydraulic institute standard, maximum efficiency can be achieved when the specific speed is around 2500 NsUS.

Reciprocating displacement pump is one in which a plunger or piston displaces a given volume of fluid for each stroke. The basic principle of a reciprocating pump is that a solid will displace an equal volume of liquid. For example, when an ice cube is dropped into a glass of water, the volume of water that spills out of the glass is equal to the submerged volume of the ice cube. All reciprocating pumps have a fluid-handling portion, commonly called the liquid end.

Power pump is a constant-speed, constant-torque, and nearly constant-capacity reciprocating machine whose plungers or pistons are driven through a crankshaft from an external source. The pump's capacity fluctuates with the number of plungers or pistons. In general, the higher the number, less is the capacity variation at a given rpm. The pump is designed for a specific speed, pressure, capacity, and horsepower. The pump can be applied to horsepower conditions less than the specific design point, but at a sacrifice of the most economical operating condition.

Diaphragm pumps are displacement pumps with flexible membranes clamped at their peripheries in sealing engagement with a stationary housing. The central portion moves in a reciprocating manner through mechanical means, such as a crank or an eccentric cam or by fluid means, such as compressed air or liquid under alternating pressure. An inlet check valve and an outlet check valve control the flow of pumped liquid into and out of the pumping chamber. A distinguishing feature of all diaphragm pumps is that they have no seals or packing and can be used in applications requiring zero leakage. They are also self-priming and can run dry without damage. In single-diaphragm pumps, the pumped liquid can have a lot of inertia if the suction and discharge lines are relatively long. A pumping cycle consists of an inlet stoke and a discharge stroke. A simple accumulator on the suction (inlet) side of the pump will allow the pump to draw liquid from the accumulator while it simultaneously draws liquid through the suction line. If the discharge line from the pump is relatively long, the inertia of the liquid can be great, as mentioned above, and can impose severe loads on the diaphragm and cranking means as the diaphragm enters the discharge stroke of a complete cycle.

Screw pumps are a special types of rotary positive displacement pumps in which the flow through the pumping elements is truly axial. The liquid is carried between screw threads on one or more rotors and is displaced axially as the screws rotate and mesh. In all other rotary pumps the liquid is forced to travel circumferentially, thus giving the screw pump with its unique axial flow pattern and low internal velocities a number of advantages in many applications where liquid agitation or churning is objectionable.

The applications of screw pumps cover a diversified range of markets: navy, marine, and utilities fuel oil service; marine cargo; industrial oil burners; lubricating oil service; chemical processes; petroleum and crude oil industries; power hydraulics of navy and machine tools; and many others. The screw pump can handle liquids in a range of viscosities, from molasses to gasoline, as well as synthetic liquids in a pressure range from 50 to 5000 lb/in$^2$ (3.5 to 350 bar) and flows up to 5000 gal/min. (1135 m$^3$/hr). Because of the relatively low inertia of their rotating parts, screw pumps are capable of operating at higher speeds than other rotary or reciprocating pumps of comparable displacement. Some turbine-attached lubricating oil pumps operate at 10,000 rpm and even higher. Screw pumps, like other rotary positive displacement pumps, are self-priming and have a delivery flow characteristics which is essentially independent of pressure.

Rotary pumps are rotary positive displacement pumps in which the main pumping action is caused by relative movement between the rotating and stationary elements of the pump. The rotary motion of these pumps distinguishes them from reciprocating positive displacement pumps, in which the main motion of moving elements is reciprocating. The positive displacement nature of the pumping action of rotary pumps distinguishes them from the general class of centrifugal pumps, in which liquid displacement and pumping action depend in large part on developed liquid velocity. It is characteristic of rotary pumps, as positive displacement pumps, that the amount of liquid displaced by each revolution is independent of speed. Also, it is characteristic of rotary pumps that a time-continuous liquid seal of sorts is maintained between the inlet and outlet ports by the action and position of the pumping elements and the close running clearances of the pump. Hence rotary pumps generally do not require inlet and outlet valve arrangements, as reciprocating pumps do.

Rotary pumps are useful in handling both fluids and liquids, where fluid is a general term that includes liquids, gases, vapours, and mixtures thereof, and sometimes solids in suspension, and where liquid is a more specific term that is limited to true liquids which are relatively incompressible and relatively free of gases, vapours, and solids.

### 6.6.1 Agricultural pumps

With enhanced irrigation and mechanisation in agricultural sector, the share of energy consumption— especially electricity has been rapidly increasing during the past decade. A major share of this energy is consumed by irrigation pumping systems, which operate at low energy efficiency.

The consumption of direct commercial energy in the agricultural sector is largely for two activities, viz. (i) mechanised land preparation, and (ii) mechanised life irrigation. The mechanised life irrigation comprises operation of electric and diesel powered pumps for extracting groundwater for irrigation purposes. These pumping systems include besides the pump, other components like motor, suction and delivery pipes, valves, pipe fittings, etc. The pumps and their appurtenances are manufactured by different agencies and hence have varying operational characteristics. In view of the fact that the energy consumption by these pumps is directly related to their operational efficiency, it is necessary to improve their efficiency through suitable rectification measures. As a first step towards achieving this objective, it is necessary to assess the current operational features of the agricultural pumping systems, the geological and agricultural factors affecting their performance, and the institutional arrangements for rectification of these pumping systems.

Factors influencing energy consumption include: (i) groundwater status, (ii) agricultural situation, (iii) performance status of pumping system, (iv) level of electricity supply, and (v) awareness among farmers.

## 6.7 Belt drives

Belts can be used to transmit power from one shaft to another, and at the same time obtain a reduction or increase in rpm. As a rule the shafts are parallel; however, by proper design and at lower loads they can be placed at an angle. Most flat belts used in industry are made of either duck or leather. Canvas or duck belts are protected from erosion by a rubber covering. For special conditions, flat belts can be made from almost any material that can be bent around pulleys.

Under normal conditions, flat belts operate at speeds below 3000 ft/min. However, carefully designed installations have been operated successfully at belt speeds as high 6000 ft/min. Belts experience a critical speed phenomenon which is evidenced by the pulleys 'riding' from side to side or by violet 'flapping' of the slack side of the belt. The critical speed of an installation is a function of the geometry of the installation, belt characteristics, and tension. Thus, when critical conditions occur they are corrected by changing some of these parameters.

# 7

# Nanotechnology and solar power

## 7.1 Introduction

Nanotechnology provides essential improvement potentials for the development of both conventional energy sources (fossil and unclear fuels) and renewable energy sources like geothermal energy, sun, wind, water, tides or biomass. Breakthroughs in nanotechnology open up the possibility of moving beyond our current alternatives for energy supply by introducing technologies that are more efficient, inexpensive, and environmentally sound. According to various researchers and authors, nanotechnologies provide the potential to enhance energy efficiency across all branches of industry and to economically leverage renewable energy production through new technological solutions and optimised production technologies. Nanotechnology innovations could impact each part of the value-added chain in the energy sector.

Nanotechnology has the potential for significant impact at all stages of the energy value chain. A number of oil companies are investigating ways in which nanotechnology can improve the effectiveness of oil drilling. One of the main applications for nanotechnology in energy generation is solar photovoltaics, with thin film solar technologies, using CIGS and CdTe, and dye-sensitised solar cells. Energy storage is also affected by nanotechnology. Novel electrode materials are already commercially available and are increasing the power density and stability of batteries.

The primary driver—and it is of immense importance—is the increasing awareness of the threat of climate change, and a policy climate which reflects that. Companies which are developing energy technologies that do not produce significant quantities of $CO_2$; generating energy from the sun, the wind, water and vegetable matter; know that they will have access to a supportive policy environment and an investor community which is very much focused on developing these technologies. Currently two applications of nanotechnology for energy are considered; solar photovoltaics, and batteries.

Solar photovoltaic (PV) cells convert sunlight to electricity. As an indication of the market potential, some projections call for 12 per cent of Europe's electricity needs to be satisfied by solar generation by 2020, a total of 420 terawatt hours (TWh). Solar PV applications can be divided into grid-connected, off-grid systems, and portable applications. A number of companies have commercial products and development activities focused on nanotechnology-based solar technologies. The battery market is expected to grow substantially in the coming years. This is partially driven by growth in existing battery applications—particularly laptops, 'netbooks' and mobile devices. However, the primary driver will be new applications, particularly in the automotive industry. Nanotechnology for batteries is a very active field of research and development. Nanotechnology can provide an improved solution to important functional requirements such as power density, charge/discharge efficiency, and self-discharge rate, as well as making the batteries themselves less volatile. The nanorods behave as wires because when they absorb light of a specific wavelength they generate electrons. These electrons flow through the nanorods until they reach the aluminium electrode where they are combined to form a current and are used as electricity. Another potential feature of these solar cells is that the nanorods could be 'tuned' to absorb various wavelengths of light. This could significantly increase the efficiency of the solar cell because more of the incident light could be utilised (Fig. 7.1).

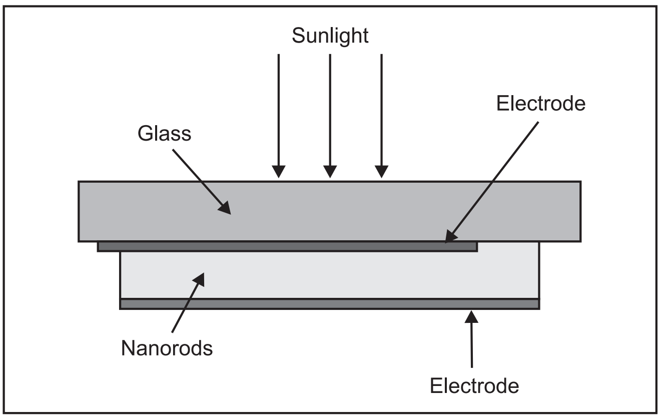



**Figure 7.1** Diagram of a nano solar cell

## 7.2 Conserve energy with nanotechnology solar panel

With the evident effects of environmental neglect, energy all over the world is becoming more and more depleted. With energy sources becoming scarce, it generally results to a stiff competition to obtain the limited sources for energy resulting to high power charges. There are several sources of energy, and some of them are even natural resources such as wind, solar, and hydro. But even if the sources of energy are natural resources and should be delivered to the people at a lower cost, still, power costs are high due to expenses incurred while generating electricity.

For several years now, scientists and researches has been looking at other means to obtain the following:

1. Minimise generation costs of energy
2. Provide energy to the people without causing any damages to the environment
3. Generate renewable and recyclable energy resources
4. Provide energy and electricity with the least possible charges
5. Deliver electricity and energy to the public at the lowest possible cost

### 7.2.1 Achieving these goals using nanotechnology solar panel

Nanotechnology aims to build important things with the use of tiny machines or by producing highly advanced, essential, and quality products using tools and techniques provided by nanotechnology.

Part of the researches being conducted is to come up with a solar panel that would accurately capture solar energy that can be utilised at home, in the office, and even in large-scale industrial areas. Although there are already solar panels available in the market today, these solar panels that are usually made of silicon panels only capture 67.4 per cent light incident or solar energy emitted by the sun. Whereas, with nanotechnology, industrial and electrical manufacturers can now produce a coating for solar panels using nanorods that can capture 96.7 per cent light incident. Nanorods used in nanotechnology solar panel looks like multi-layer funnels designed to capture light incident. The first layer absorbs the light that hits the panel at wide outer angles and turns it to a slightly narrower angle. The succeeding layers become narrower, like they are passing the light to the next layer even further as it funnels the light till it reaches the active region of the panel at a 90° angle. This process makes the solar panel securely capture the sun's energy without having to rotate with the sun. The energy market encompasses a vast range of economic activity, from the extraction of fossil fuels, generation of energy by burning coal to generate electricity, for example; distribution, and consumption. A simple value chain is shown in Fig. 7.2.

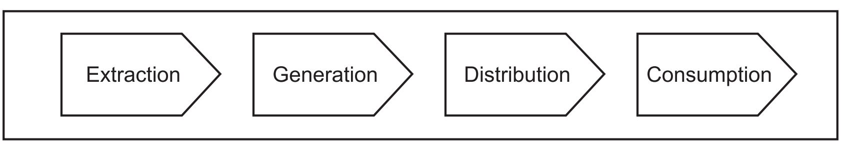



**Figure 7.2** A simple value chain

The threat of climate change has highlighted the environmental damage caused by a build up of carbon dioxide in the atmosphere. A substantial proportion of $CO_2$ is generated by activities in this energy value chain; burning fossil fuels in a power plant, a factory or a vehicle. Therefore, and with varying degrees of success, renewable energy sources are being introduced.

The macro-level consumption figures obscure growth in renewable energies, albeit from a fairly low base. For example, 2008 saw wind energy capacity grow by 28.8 per cent to 120.8 GW, with 27 GW coming on stream during the year. The market value of the wind industry is €36.5 billion, and it employs 0.4 Millions people. A third of new capacity was installed in Asia, doubling China's capacity to 12.2 GW. The European Photovoltaics Industry Association estimated that installed solar PV capacity in 2007 was 2.25 GW, and that the amount installed per year would increase to 7.3 GW by 2012. Hydroelectric power generation accounts for energy consumption of 29,728 quadrillion BTUs. This is fractionally more than the amount of energy produced by nuclear generation.

Efforts to price in the effect of $CO_2$ emissions, including the EU Emission Trading Scheme, increase the costs of fossil fuel usage, further driving adoption of alternative technologies. There are also other pressures beyond climate change on the current energy economy. The world's oil resources are finite; as oil becomes more challenging to extract, prices will rise. Post-extraction, there is a global shortage in refining capacity to turn crude oil into usable petroleum products.

## 7.3 Nanotechnology for energy extraction

Technologies include sensors that can be injected into oil reservoirs in order to provide information about the location, consistency and presence of oil deposits. Nanotechnology could also be used in the process of converting crude oil to petroleum; a filter which is composed of carbon nanotubes was found to filter large hydrocarbons from oil. One of the main applications for nanotechnology in energy generation is solar photovoltaics. Thin film solar technologies, using CIGS and CdTe, now account for 10 per cent new solar installations, and are a very active area of development; especially in production optimisation. Dye-sensitised solar cells are another promising technology area, and dye-solar has already given rise to commercial products, albeit in far smaller quantities than thin film approaches. Nanotechnology has the potential to generate step changes in the efficiency and production cost of solar. Nanotechnology can also assist in other areas of energy generation. Mechanical methods; wind turbines, and gas turbines, can benefit from improved efficiency due to material innovation. CNT composite material for wind turbine blades can prevent shearing and increase the lifetime of the turbine. Sensors on a turbine blade could detect build up of fouling and increase preventative maintenance.

### 7.3.1 Supply

Energy storage is also affected by nanotechnology. Novel electrode materials are already commercially available and are increasing the power density and stability of batteries. Retrofitting nano-enabled batteries to hybrid 'Toyota Prius' is increasing their range (and therefore their attractiveness). More generally, improvements in battery technology will increase the speed with which electric vehicles and hybrid-electric vehicles can take over from conventional combustion engines. Fuel cells are another area that will benefit from nanotechnology innovations. The use of carbon nanotubes in the catalyst support structure as a replacement for metal membranes allows for higher temperature operation.

### 7.3.2 Consumption

Finally and more indirectly, nanotechnology can also reduce energy consumption. Vehicles whose chassis is made from more lightweight materials will consume less energy; machinery which employs nanotechnology in low friction bearings or lubricants will be more energy efficient to operate. Solid state lighting as a replacement for incandescent lighting reduces energy consumption, and also provides a positive feedback loop in which lower power requirements can be satisfied with local renewable energy sources—such as a roof mounted solar cell.

## 7.4 Drivers and barriers to innovation

### 7.4.1 Drivers for innovation

The primary driver—and it is of immense importance—is the increasing awareness of the threat of climate change, and a policy climate which reflects that. Companies which are developing energy technologies that do not produce significant quantities of $CO_2$; generating energy from the sun, the wind, water and vegetable matter; know that they will have access to a supportive policy environment and an investor community which is very focused on developing these technologies. Subsidies decrease the cost of renewable energies; cap and trade schemes increase the price of energy produced with fossil fuels. However, there remains a price gap in which fossil fuels are substantially lower cost for important uses such as electricity generation. An important driver for the development of new technologies is therefore improvements in their cost-effectiveness; in the case of photovoltaics, this comes from reducing material costs, increasing production efficiency, and increasing the efficiency of PV cells in use.

### 7.4.2 Barriers to innovation

The largest energy companies are still those which extract and process fossil fuels. Whilst they may still invest in new technologies—and some are quite supportive of renewable energy—there is not as much substantial industrial investment in energy technology as there is in ICT, for example. However, this is offset by the large amounts of public funding that are being directed towards energy research.

## 7.5 Solar photovoltaics

The dominant current technology for the production of solar PV is amorphous or single crystal silicon. This accounts for over 90 per cent of current solar PV production. The technology sector identifies several nanotechnology-based approached to solar PV, which are differing stages of market readiness:

*Thin-film:* This technology area is often described as 'second generation' solar PV. Materials used include amorphous silicon (aSi), copper indium gallium sellenide (CIGS), and cadmium telluride (CdTe). Thin-film solar PV is currently in production.

*Emerging approaches:* The third generation of solar PV includes emerging approaches such as dye-sensitive solar cells (DSSC) and quantum dots. DSSC and conducting polymer PV cells are currently in production, though seemingly in much lower quantities that crystalline silicon and thin film.

The impact of nanotechnology may be to lower the cost of solar PV by reducing material requirements or by introducing more efficient manufacturing methods. It may also enable novel applications of solar PV technology, such as integration with building materials or even clothing.

### 7.5.1 Short application description

Solar photovoltaic (PV) cells convert sunlight to electricity. Applications range from very large grid-connected solar power plants to small solar cells for portable devices. A combination of factors, including government subsidies, cost reductions, and the increasing cost of alternatives contributes to substantial growth in the solar PV market. As an indication of the market potential, some projections call for 12 per cent of Europe's electricity needs to be satisfied by solar generation by 2020, a total of 420 terawatt hours (TWh). Solar PV applications can be divided into grid-connected, off-grid systems, and portable applications.

## *Grid-connected solar PV*

The application category includes solar PV installations that are connected to the electricity grid. These range from solar power plants which are capable of generating sufficient electricity to power thousands of homes, to installations in industrial facilities, retail spaces and private homes. A number of companies have invested in the production of solar power plants. Grid-connected solar replaces other sources of electricity generation; typically coal or gas-fired power stations. Industrial and home installations may be used to satisfy local electricity demand, and to supply additional power at times of peak demand; the classic example being their use to power air conditioning units on hot, sunny summer days. Grid connectivity also enables excess local electricity production to be supplied to the power grid, although this also requires billing and metering mechanisms and a device to convert the current. Grid-connected solar PV has been the engine of solar growth over the last decade, and accounts for a very high proportion of all solar cells sold. The quantities involved render this a large-scale, manufacturing intensive business. Many of the larger companies in this space, such as Sharp or Kyocera, have experience in mass production of glass or displays, and have applied this experience to the production of crystalline silicon PV.

## *Off-grid systems*

Although this category includes a range of applications, off-grid systems are generally smaller scale than grid-connected PV. Off-grid solar PV may be used to provide power in places which are not connected to the electricity grid, in developing countries or in rural areas of developed countries. Electrifying rural areas is not only an economic opportunity, and also has wider societal benefits.

A significant application is the use of off-grid solar to power utilities, such as cell towers for mobile telephone networks. A combination of the power requirement of telecom base stations, and their location on high ground, make off-grid solar PV an attractive power source. Similarly, solar PV cells may be used to power street lighting, traffic lights, and signage. This application area reduces the cost and complexity of connecting these utilities to the electricity grid.

## *Portable devices*

The most ubiquitous application of solar PV is their use to replace batteries as a power source for portable devices such as calculators and watches. This application area currently accounts for a very small proportion of the total global PV market. Despite their ubiquity, these are a small, commoditised component of a low cost device, and therefore the value is low:

| Category | Existing application examples |
|---|---|
| Grid-connected | Solar power plants: industrial, retail and domestic applications |
| Off-grid | Rural electrification: utility in lighting, signage and telecoms |
| Portable | Devices: watches, calculators |

## *Nanotechnology-enabled novel applications*

The current dominant technology, silicon, limits the form factor of solar PV to inflexible, fragile flat panels. Whilst this is adequate for most current applications, especially large-scale grid connected solar; there are novel applications that would be enabled by new form factors.

## *Reduced material costs*

Until recently, limited supply and commensurate high cost of silicon has been a major factor in increasing the cost of crystalline silicon PV. There is some evidence that this pressure will ease in coming years, though it may also be the case that the bottleneck simply shifts down the value chain to wafer production. Whilst this factor will not alter if one costly element (silicon) is replaced with another (indium), several new approaches either employ less rare materials or reduce the quantities needed.

## *Low-cost manufacturing*

There are two elements at work here. Production of crystalline silicon is being scaled up, with major manufacturers opening larger and larger facilities; Solar World has expanded its main German facility to production capacity of 1GW. This should result in manufacturing economies of scale.

Meanwhile, production processes for thin-film solar are being improved. Nanosolar, which builds thin-film CIGS cells, claims that it has optimised several different elements of the production process including applying CIGS as a printable ink using a roll to roll process. The key question is to what extent rapid, incremental reductions in the cost of manufacturing crystalline silicon cells are outweighed by the inherent efficiencies in print-like production.

### *Improved efficiency*

The efficiency of a PV cells is a measure of how well it converts absorbed light into electrical energy, and is typically expressed as a percentage. Whilst this is an important measure amongst the research community, it is just one element of the key metric, cost per kilowatt hour. Currently the highest efficiencies are obtained by concentrator PV (CPV) cells, which are capable of generating conversion efficiencies of around 40 per cent (a European record of 39.7 per cent was achieved by Fraunhofer ISE in 2008). Efficiencies achieved by other technology approaches are shown in Table 7.1.

The conversion efficiency of the specific technology used is just one element of the overall system efficiency, it being further affected by the packaging and other elements of the photovoltaic system.

*20 year* + installed lifetime: Clearly one of the most important factors in calculating the life-cycle cost of PV cells is how its efficiency will change over time (and how long it takes until it simply fails to operate). The target lifetime for a PV cell is at least 20 years, in a temperature range of –40° to 85°C, and many manufactures issue warrantees to this effect. Durability is a particular issue with organic approaches; degradation of conducting polymers is a well-studied phenomenon.

**Table 7.1** Comparison of efficiency levels achieved by solar PV technologies.

| Technology | Highest recorded efficiency (%) |
|---|---|
| Concentrator PV | 40 |
| Crystalline silicon | 24 |
| Thin-film–CIGS | 19 |
| Thin-film–CdTe | 16 |
| Thin-film–aSi | 12 |
| Organic PV | 5 |

### *Drivers for market size increase of solar PV*

The growth of solar PV has been driven by the factors; reduced costs (via subsidy), and an increase in the cost of alternatives due to rising fuel costs and emission pricing.

## *Drivers affecting market share of nanotechnology-enabled solar PV*

Two factors will impact the extent to which nanotechnology-based approaches become price competitive with crystalline silicon; cost of materials, and cost of production.

Silicon shortage in 2008 may give way to oversupply by 2012. Renewable Energy Corporation, an integrated producer of silicon, wafers, cells and modules, projects that polysilicon production capacity will increase from under 50,000 MT in 2008 to 125–1,60,000 MT in 2012. This would exceed their projection of demand for polysilicon in 2012, potentially leading to a price drop. This is in part because the solar industry currently competes with the semiconductor industry for high grade silicon, but in future ‘solar grade’ silicon will emerge with a distinct supply chain.

Restrictions on capital expenditure will drive low cost manufacturing. Manufacturing expenses account for a small proportion of total solar PV cost on an ongoing basis (materials are the largest cost item). However, the costs of building a manufacturing plant are substantial, and during a period where capital will be difficult to access, lower cost manufacturing methods could gain market share.

## *Effect of nanotechnology-enabled products on the solar PV value chain*

The current value chain for crystalline silicon solar PV is shown in Fig. 7.3.

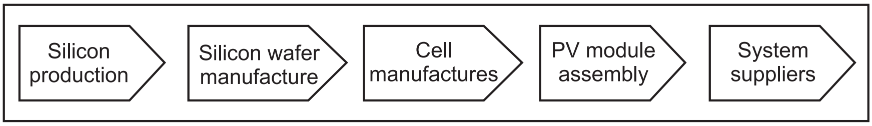



**Figure 7.3** Value chain for crystalline silicon solar PV

Thin-film solar PV will reduce the importance of silicon production and wafer manufacture, given the flexibility to apply onto a number of substrates. However approaches which continue to use rare metals (such as CIGS) could simply replace the silicon supply bottleneck with an Indium shortage.

# 8
# Wind energy

## 8.1 Introduction

Wind is simply air in motion. It is caused by the uneven heating of the earth's surface by the sun. Because the earth's surface is made of very different types of land and water, it absorbs the sun's heat at different rates. One example of this uneven heating can be found in the daily wind cycle.

During the day, the air above the land heats up more quickly than the air over water. The warm air over the land expands and rises, and the heavier, cooler air rushes in to take its place, creating wind. At night, the winds are reversed because the air cools more rapidly over land than over water.

In the same way, the atmospheric winds that circle the earth are created because the land near the earth's equator is heated more by the sun than the land near the North and South Poles. Today, wind energy is mainly used to generate electricity. Wind is a renewable energy source because the wind will blow as long as the sun shines.

Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow or motion energy, when 'harvested' by modern wind turbines, can be used to generate electricity.

The terms 'wind energy' or 'wind power' describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity to power homes, businesses, schools, and the like.

*Wind turbines:* Wind turbines, like aircraft propeller blades, turn in the moving air and power an electric generator that supplies an electric current. Simply stated, a wind turbine is the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.

Modern wind turbines fall into two basic groups; the horizontal-axis variety, like the traditional farm windmills used for pumping water, and the vertical-axis design, like the eggbeater-style Darrieus model, named after its French inventor. Most large modern wind turbines are horizontal-axis turbines.

*Turbine components:* Horizontal turbine components include:

1. Blade or rotor, which converts the energy in the wind to rotational shaft energy.
2. A drive train, usually including a gearbox and a generator.
3. A tower that supports the rotor and drive train.
4. Other equipment, including controls, electrical cables, ground support equipment, and interconnection equipment.

Wind turbines are often grouped together into a single wind power plant, also known as a wind farm, and generate bulk electrical power. Electricity from these turbines is fed into a utility grid and distributed to customers, just as with conventional power plants.

Wind turbines are available in a variety of sizes, and therefore power ratings. The largest machine has blades that span more than the length of a football field, stands 20 building stories high, and produces enough electricity to power 1400 homes. A small home-sized wind machine has rotors between 8 and 25 ft in diameter and stands upwards of 30 ft and can supply the power needs of an all-electric home or small business. Utility-scale turbines range in size from 50 to 750 kW. Single small turbines, below 50 kW, are used for homes, telecommunications dishes or water pumping.

*A renewable non-polluting resource:* Wind energy is a free, renewable resource, so no matter how much is used today, there will still be the same supply in the future. Wind energy is also a source of clean, non-polluting, electricity.

*Cost issues:* The technology requires a higher initial investment than fossil-fuelled generators. Roughly 80 per cent of the cost is the machinery, with the balance being site preparation and installation. If wind generating systems are compared with fossil-fuelled systems on a 'life-cycle' cost basis (counting fuel and operating expenses for the life of the generator), however, wind costs are much more competitive with other generating technologies because there is no fuel to purchase and minimal operating expenses.

*Environmental concerns:* Although wind power plants have relatively little impact on the environment compared to fossil fuel power plants, there is some concern over the noise produced by the rotor blades, aesthetic (visual) impacts, and birds and bats having been killed (avian/bat mortality) by flying into the rotors. Most of these problems have been resolved or greatly reduced through technological development or by properly citing wind plants.

*Supply and transport issues:* The major challenge to using wind as a source of power is that it is intermittent and does not always blow when electricity is needed. Wind cannot be stored (although wind-generated electricity can be stored, if batteries are used), and not all winds can be harnessed to meet the timing of electricity demands. Further, good wind sites are often located in remote locations far from areas of electric power demand (such as cities). Finally, wind resource development may compete with other uses for the land, and those alternative uses may be more highly valued than electricity generation. However, wind turbines can be located on land that is also used for grazing or even farming.

## 8.2 Wind power

Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electricity, windmills for mechanical power, wind pumps for water pumping or drainage, or sails to propel ships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation, and the cost per unit of energy produced is similar to the cost for new coal and natural gas installations.

At the end of 2010, worldwide nameplate capacity of wind-powered generators was 197 gigawatts (GW). Wind power now has the capacity to generate 430 TWh annually, which is about 2.5 per cent of worldwide electricity usage. Over the past five years the average annual growth in new installations has been 27.6 per cent. Wind power market penetration is expected to reach 3.35 per cent by 2013 and 8 per cent by 2018. Several countries have already achieved relatively high levels of wind power penetration, such as 21 per cent of stationary electricity production in Denmark, 18 per cent in Portugal, 16 per cent in Spain, 14 per cent in Ireland and 9 per cent in Germany in 2010. As of 2011, 83 countries around the world are using wind power on a commercial basis.

Although a variable source of power, the intermittency of wind seldom creates problems when using wind power to supply up to 20 per cent of total electricity demand, but as the proportion rises, increased costs, a need to use storage such as pumped-storage hydroelectricity, upgrade the grid or a lowered ability to supplant conventional production may occur. Power management techniques such as excess capacity, storage, dispatchable backing supply (usually natural gas), exporting and importing power to neighbouring areas or reducing demand when wind production is low, can mitigate these problems.

A large wind farm may consist of several hundred individual wind turbines which are connected to the electric power transmission network. Offshore wind power can harness the better wind speeds that are available offshore compared to on land, so offshore wind power's contribution in terms of electricity supplied is higher. Small onshore wind facilities are used to provide electricity to isolated locations and utility companies increasingly buy back surplus electricity produced by small domestic wind turbines. The construction of wind farms is not universally welcomed because of their visual impact, but any effects on the environment from wind power are generally less problematic than those of any other power source.

## 8.3 Wind energy

The earth is unevenly heated by the sun, such that the poles receive less energy from the sun than the equator; along with this, dry land heats up (and cools down) more quickly than the seas do. The differential heating drives a global atmospheric convection system reaching from the earth's surface to the stratosphere which acts as a virtual ceiling. Most of the energy stored in these wind movements can be found at high altitudes where continuous wind speeds of over 160 km/hr (99 mph) occur. Eventually, the wind energy is converted through friction into diffuse heat throughout the earth's surface and the atmosphere.

The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. The most comprehensive study as of 2008 found the potential of wind power on land and near-shore to be 72 TW, equivalent to 54,000 MToE (million tons of oil equivalent) per year or over five times the world's current energy use in all forms. The potential takes into account only locations with mean annual wind speeds ≥6.9 m/s at 80 m. The study assumes six 1.5 MW, 77 m diameter turbines per square kilometre on roughly 13 per cent of the total global land area (though that land would also be available for other compatible uses such as farming). The practical limit to exploitation of wind power will be set by economic and environmental factors, since the resource available is far larger than any practical means to develop it.

### 8.3.1 Distribution of wind speed

Distribution of wind speed (red) and energy (blue) for all of 2007 at the Lee Ranch facility in Colorado. The histogram shows measured data, while the curve is the Rayleigh model distribution for the same average wind speed.

The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there.

To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data. Different locations will have different wind speed distributions. The Weibull model closely mirrors the actual distribution of hourly wind speeds at many locations. The Weibull factor is often close to 2 and therefore a Rayleigh distribution can be used as a less accurate, but simpler model.

### 8.3.2 Electricity generation

In a wind farm, individual turbines are interconnected with a medium voltage (often 34.5 kV), power collection system and communications network. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system. The surplus power produced by domestic microgenerators can, in some jurisdictions, be fed into the network and sold to the utility company, producing a retail credit for the microgenerators' owners to offset their energy costs.

#### *Grid management*

Induction generators, often used for wind power, require reactive power for excitation so substations used in wind-power collection systems include substantial capacitor banks for power factor correction. Different types of wind turbine generators behave differently during transmission grid disturbances, so extensive modelling of the dynamic electromechanical characteristics of a new wind farm is required by transmission system operators to ensure predictable stable behaviour during system faults. In particular, induction generators cannot support the system voltage during faults, unlike steam or hydro turbine-driven synchronous generators.

Doubly fed machines generally have more desirable properties for grid interconnection. Transmission systems operators will supply a wind farm developer with a grid code to specify the requirements for interconnection to the transmission grid. This will include power factor, constancy of frequency and dynamic behaviour of the wind farm turbines during a system fault.

#### *Capacity factor*

Since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the capacity factor. Typical capacity factors are 20–40 per cent, with values at the upper end of the range in particularly favourable sites. For example, a 1 MW turbine with a capacity factor of 35 per cent will not produce 8760 MW·h in a year (1 × 24 × 365), but only 1 × 0.35 × 24 × 365 = 3066 MW·h, averaging to 0.35 MW. Online data is available for some locations and the capacity factor can be calculated from the yearly output.

Unlike fuelled generating plants, the capacity factor is affected by several parameters, including the variability of the wind at the site, but also the generator size—having a smaller generator would be cheaper and achieve higher capacity factor, but would make less electricity (and money) in high winds. Conversely a bigger generator would cost more and generate little extra power and, depending on the type, may stall out at low wind speed. Thus an optimum capacity factor can be used, which is usually around 20–35 per cent.

## *Penetration*

Wind energy 'penetration' refers to the fraction of energy produced by wind compared with the total available generation capacity. There is no generally accepted 'maximum' level of wind penetration. The limit for a particular grid will depend on the existing generating plants, pricing mechanisms, capacity for storage or demand management, and other factors. An interconnected electricity grid will already include reserve generating and transmission capacity to allow for equipment failures; this reserve capacity can also serve to regulate for the varying power generation by wind plants. Studies have indicated that 20 per cent of the total electrical energy consumption may be incorporated with minimal difficulty. These studies have been for locations with geographically dispersed wind farms, some degree of dispatchable energy or hydropower with storage capacity, demand management, and interconnection to a large grid area export of electricity when needed. Beyond this level, there are few technical limits, but the economic implications become more significant. Electrical utilities continue to study the effects of large (20 per cent or more) scale penetration of wind generation on system stability and economics.

## *Intermittency and penetration limits*

Electricity generated from wind power can be highly variable at several different time-scales: from hour to hour, daily, and seasonally. Annual variation also exists, but is not as significant. Related to variability is the short-term (hourly or daily) predictability of wind plant output. Like other electricity sources, wind energy must be 'scheduled'. Wind power forecasting methods are used, but predictability of wind plant output remains low for short-term operation. Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, this variability can present substantial challenges to incorporating large amounts of wind power into a grid system. Intermittency and the non-dispatchable nature of wind energy production can raise costs for regulation, incremental operating reserve, and (at high penetration levels) could require an increase in the already existing energy demand management, load shedding or storage solutions or system interconnection with HVDC cables. At low levels of wind penetration, fluctuations in load and allowance for failure of large generating units requires reserve capacity that can also regulate for variability of wind generation. Wind power can be replaced by other power stations during low wind periods. Transmission networks must already cope with outages of generation plant and daily changes in electrical demand. Systems with large wind capacity components may need more spinning reserve (plants operating at less than full load).

Pumped-storage hydroelectricity or other forms of grid energy storage can store energy developed by high-wind periods and release it when needed. Stored energy increases the economic value of wind energy since it can be shifted to displace higher cost generation during peak demand periods. The potential revenue from this arbitrage can offset the cost and losses of storage; the cost of storage may add 25 per cent to the cost of any wind energy stored, but it is not envisaged that this would apply to a large proportion of wind energy generated.

### *Capacity credit and fuel saving*

Many commentators concentrate on whether or not wind has any 'capacity credit' without defining what they mean by this and its relevance. Wind does have a capacity credit, using a widely accepted and meaningful definition, equal to about 20 per cent of its rated output (but this figure varies depending on actual circumstances). This means that reserve capacity on a system equal in MW to 20 per cent of added wind could be retired when such wind is added without affecting system security or robustness. But the precise value is irrelevant since the main value of wind is its fuel and $CO_2$ savings.

### *Installation placement*

Good selection of a wind turbine site is critical to economic development of wind power. Aside from the availability of wind itself, other factors include the availability of transmission lines, value of energy to be produced, cost of land acquisition, land use considerations, and environmental impact of construction and operations. Offshore locations may offset their higher construction cost with higher annual load factors, thereby reducing cost of energy produced. Wind farm designers use specialised wind energy software applications to evaluate the impact of these issues on a given wind farm design.

## 8.4 Energy from the wind

Windmills have been used for many centuries for pumping water and milling grain. The discovery of the internal combustion engine and the development of electrical grids caused many windmills to disappear in the early part of this century.

However, in recent years there has been a revival of interest in wind energy and attempts are underway all over the world to introduce cost-effective wind energy conversion systems for this renewable and environmentally benign energy source.

In developing countries, wind power can play a useful role for water supply and irrigation (wind pumps) and electrical generation (wind generators). These two variants of windmill technology are discussed in separate technical briefs. This brief gives a general overview of the resource and of the technology of extracting energy from the wind.

### 8.4.1 Energy availability in the wind

The power in the wind is proportional to the cube of wind velocity. The general formula for wind
power is:

$$\text{Power} = \frac{\text{Energy output from array}}{\text{Energy input from sun}} \times 100$$

$$P = \tfrac{1}{2}\rho.A.v^3$$

If the velocity (v) is in m/s, then at sea level (where the density of air is 1.2 kg/m$^3$) the power in the wind is:

Power = 0.6 × $v^3$ watts per m$^2$ of rotor swept area.

This means that the power density in the wind will range from 10 W/m$^2$ at 2.5 m/s (a light breeze) to 41,000 W/m$^2$ at 40 m/s (a hurricane). This variability of the wind power resource strongly influences virtually all aspects of wind energy conversion systems design, construction, citing, use and economy.

## 8.5 Wind resource

Unfortunately, the general availability and reliability of wind speed data is extremely poor in many regions of the world. Large areas of the world appear to have mean annual wind speeds below 3 m/s, and are unsuitable for wind power systems, and almost equally large areas have wind speeds in the intermediate range (3–4.5 m/s) where wind power may or may not be an attractive option. In addition, significant land areas have mean annual wind speeds exceeding 4.5 m/s where wind power would most certainly be economically competitive.

## 8.6 Principles of wind energy conversion

There are two primary physical principles by which energy can be extracted from the wind; these are through the creation of either drag or lift force (or through a combination of the two). The difference between drag and lift is illustrated (Fig. 8.1) by the difference between using a spinaker sail, which fills like a parachute and pulls a sailing boat with the wind, and a bermuda rig, the familiar triangular sail which deflects with wind and allows a sailing boat to travel across the wind or slightly into the wind. Drag forces provide the most obvious means of propulsion, these being the forces felt by a person (or object) exposed to the wind. Lift forces are the most efficient means of propulsion but being more subtle than drag forces are not so well understood.

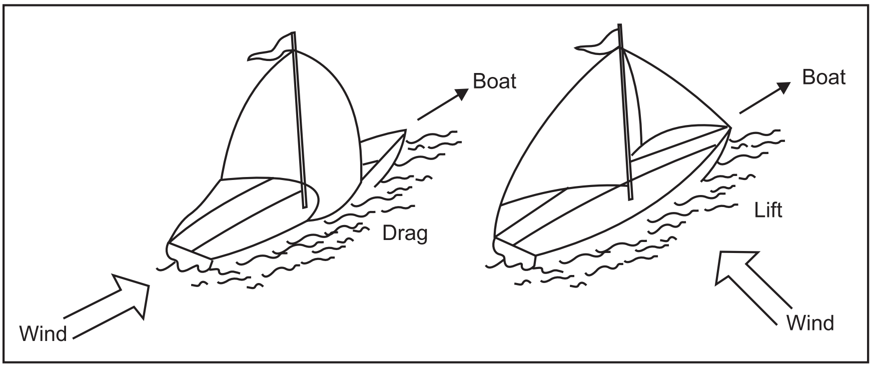



**Figure 8.1** Drag and lift forces

The basic features that characterise lift and drag are:

1. Drag is in the direction of airflow.
2. Lift is perpendicular to the direction of airflow.
3. Generation of lift always causes a certain amount of drag to be developed.
4. With a good aerofoil (Fig. 8.2), the lift produced can be more than thirty times greater than the drag.
5. Lift devices are generally more efficient than drag devices.

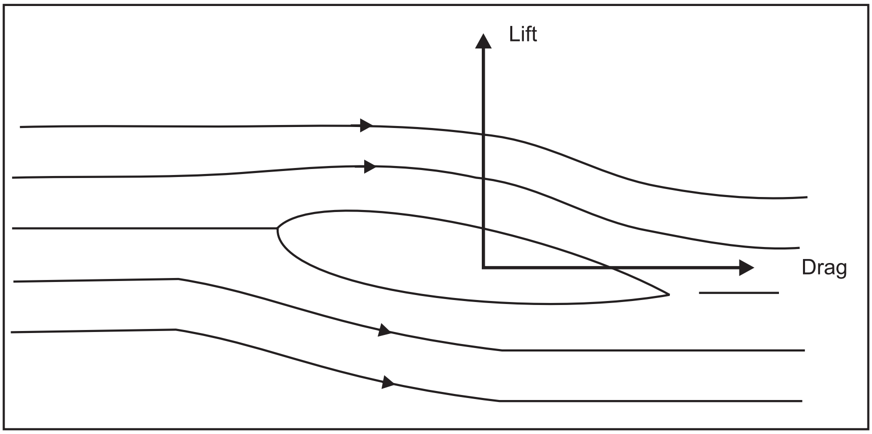



**Figure 8.2** Aerofoil

## 8.7 Types and characteristics of windmill rotors

There are two main families of windmills: vertical axis machines and horizontal axis machines. These can in turn use either lift or drag forces to harness the wind. Of these types the horizontal axis lift device represents the vast majority of successful wind machines, either ancient or modern. In fact other than a few experimental machines virtually all windmills come under this category.

There are several technical parameters that are used to characterise windmill rotors. The tip-speed ratio is defined as the ratio of the speed of the extremities of a windmill rotor to the speed of the free wind. It is a measure of the 'gearing ratio' of the rotor (Fig. 8.3). Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios and hence turn quickly relative to the wind.

$$\text{Tip speed ratio} = \frac{\text{Bade tip speed}}{\text{Wind speed}}$$

The proportion of the power in the wind that the rotor can extract is termed the coefficient of performance (or power coefficient or efficiency; symbol $C_p$) and its variation as a function of tip-speed ratio is commonly used to characterise different types of rotor. It is physically impossible to extract all the energy from the wind, without bringing the air behind the rotor to a standstill. Consequently, there is a maximum value of $C_p$ of 59.3 per cent (known as the Betz limit); although in practice, real wind rotors have maximum $C_p$ values in the range of 25–45 per cent.

Solidity is usually defined as the percentage of the circumference of the rotor which contains material rather than air.

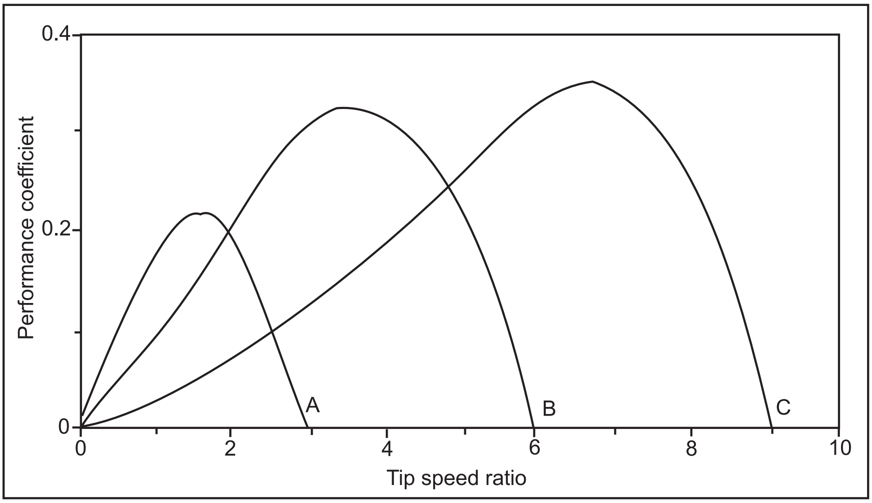



**Figure 8.3** Tip speed ratio and the performance coefficient

High-solidity machines carry a lot of material and have coarse blade angles. They generate much higher starting torque than low-solidity machines but are inherently less efficient than low-solidity machines as shown in Fig. 8.4. The extra materials also cost more money. However, low-solidity machines need to be made with more precision which leads to little difference in costs. The choice of rotor is dictated largely by the characteristic of the load and hence of the end use. These aspects are discussed separately in the technical briefs on wind pumps and wind generators. Table 8.1 compares different rotor types.

**Table 8.1** Comparison of rotor types.

| Type | Speed | Torque | Manufacture | $C_p$ | Solidity % |
|---|---|---|---|---|---|
| **Horizontal axis** | | | | | |
| Cretan sail | Low | Medium | Simple | 0.05–0.15 | 50 |
| Cambered plate fan | Low | High | Moderate | 0.15–0.30 | 50–80 |
| Moderate speed aero-generator | Moderate | Low | Moderate | 0.20–0.35 | 5–10 |
| High speed aero-generator | High | Very low | Precise | 0.30–0.45 | <5 |
| **Vertical axis** | | | | | |
| Panemone | Low | Medium | Crude | >0.10 | 50 |
| Savonius | Moderate | Medium | Moderate | 0.15 | 100 |
| Darrieus | Moderate | Very low | Precise | 0.25–0.35 | 10–20 |
| Variable geometry | Moderate | Very low | Precise | 0.20–0.35 | 15–40 |

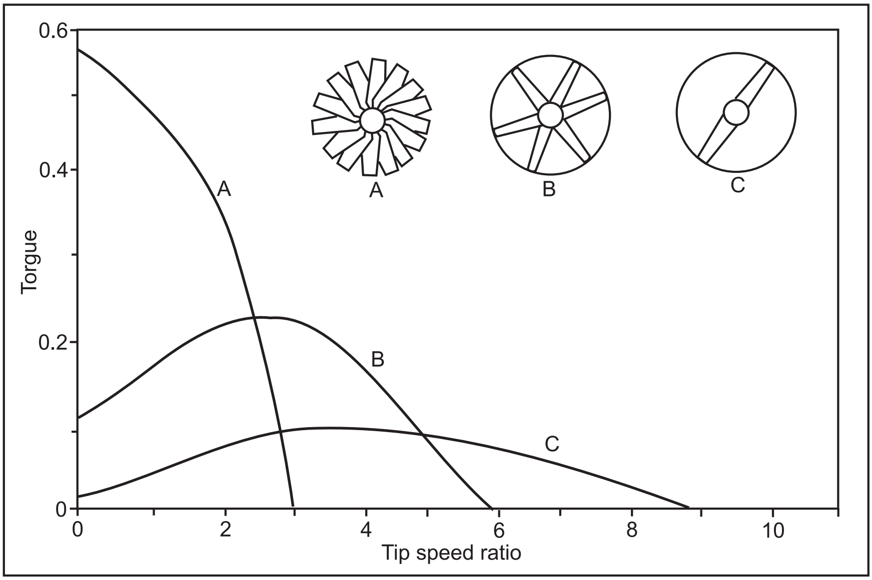



**Figure 8.4** Solidity and torque

## 8.8 Windmill performance

Although the power available is proportional to the cube of wind speed, the power output has a lower order dependence on wind speed. This is because the overall efficiency of the windmill (the product of rotor Cp, transmission efficiency and pump or generator efficiency) changes with wind speed. There are four important characteristic wind speeds:

1. The cut-in wind speed: when the machine begins to produce power.
2. The design wind speed: when the windmill reaches its maximum efficiency.
3. The rated wind speed: when the machine reaches its maximum output power.
4. The furling wind speed: when the machine furls to prevent damage at high wind speeds.

Performance data for windmills can be misleading because they may refer to the peak efficiency (at design wind speed) or the peak power output (at the rated wind speed). The data could also refer to the average output over a time period (e.g. a day or a month).

Because the power output varies with wind speed, the average output over a time period is dependent in the local variation in wind speed from hour to hour. Hence to predict the output for a given windmill one needs to have output characteristics of the windmill and the wind speed distribution curve of the site (duration at various wind speeds). Multiplying the values of both graphs for each wind speed interval and adding all the products gives the total energy output of that windmill at that site.

## 8.9 Wind speed

Wind speed or wind velocity is a fundamental atmospheric rate. Wind speed affects weather forecasting, aircraft and maritime operations, construction projects, growth and metabolism rate of many plant species, and countless other implications. Wind speed is now commonly measured with an anemometer but can also be classified using the older Beaufort scale which is based on people's observation of specifically defined wind effects.

### 8.9.1 Factors affecting wind speed

Wind speed is affected by a number of factors and situations, operating on varying scales (from micro to macro scales). These include the pressure gradient, Rossby waves and jet streams, and local weather conditions. There are also links to be found between wind speed and wind direction, notably with the pressure gradient and surfaces over which the air is found.

Pressure gradient is a term to describe the difference in air pressure between two points in the atmosphere or on the surface of the earth. It is vital to wind speed, because the greater the difference in pressure, the faster the wind flows (from the high to low pressure) to balance out the variation. The pressure gradient, when combined with the Coriolis effect and friction, also influences wind direction.

Rossby waves are strong winds in the upper troposphere. These operate on a global scale and move from West to East (hence being known as Westerlies). The Rossby waves are themselves a different wind speed from what we experience in the lower troposphere.

Local weather conditions play a key role in influencing wind speed, as the formation of hurricanes, monsoons and cyclones as freak weather conditions can drastically affect the velocity of the wind.

## 8.10 Wind turbine

A wind turbine is a device that converts kinetic energy from the wind into mechanical energy. If the mechanical energy is used to produce electricity, the device may be called a wind generator or wind charger. If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump. Developed for over a millennium, today's wind turbines are manufactured in a range of vertical and horizontal axis types. The smallest turbines are used for applications such as battery charging or auxiliary power on sailing boats; while large grid-connected arrays of turbines are becoming an increasingly large source of commercial electric power (Fig. 8.5).

**Figure 8.5** Wind farm

Wind turbines in locations with constantly high wind speeds bring best return on investment. With a wind resource assessment it is possible to estimate the amount of energy the wind turbine will produce.

A quantitative measure of the wind energy available at any location is called the wind power density (WPD). It is a calculation of the mean annual power available per square metre of swept area of a turbine, and is tabulated for different heights above ground. Calculation of wind power density includes the effect of wind velocity and air density. Colour-coded maps are prepared for a particular area described, for example, as 'mean annual power density at 50 m'.

### 8.10.1 Types of wind turbines

Wind turbines can rotate about either a horizontal or a vertical axis, the former being both older and more common.

## Horizontal axis

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

## Subtypes

(a) *12th-century windmills:* These squat structures, typically (at least) four bladed, usually with wooden shutters or fabric sails, were developed in Europe. These windmills were pointed into the wind manually or via a tail-fan and were typically used to grind grain. In the Netherlands they were also used to pump water from low-lying land, and were instrumental in keeping its polders dry.

(b) *19th-century windmills:* The Eclipse windmill factory was set up around 1866 in Beloit, Wisconsin and soon became successful building mills for pumping water on farms and for filling railroad tanks. Other firms like Star, Dempster, and Aeromotor also entered the market. Hundreds of thousands of these mills were produced before rural electrification and small numbers continue to be made. They typically had many blades, operated at tip speed ratios not better than one, and had good starting torque. Some had small direct-current generators used to charge storage batteries, to provide power to lights or to operate a radio receiver.

(c) *Modern wind turbines:* Turbines used in wind farms for commercial production of electric power are usually three-bladed and pointed into the wind by computer-controlled motors. These have high tip speeds of up to six times the wind speed, high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually coloured light gray to blend in with the clouds and range in length from 20 to 40 m (65 to 130 ft) or more. The tubular steel towers range from 200 to 300 ft (60 to 90 m) tall. The blades rotate at 10–22 revolutions per minute. A gear box is commonly used to step up the speed of the generator, although designs may also use direct drive of an annular generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with shutdown features to avoid damage at high wind speeds.

## *Advantages of HAWT*

1. Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.
2. The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every 10 m up, the wind speed can increase by 20 per cent and the power output by 34 per cent for every 10 m in elevation.
3. High efficiency, since the blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.
4. The face of a horizontal axis blade is struck by the wind at a consistent angle regardless of the position in its rotation. This results in a consistent lateral wind loading over the course of a rotation, reducing vibration and audible noise coupled to the tower or mount.

## *Disadvantages of HAWT*

1. HAWTs have difficulty operating in near ground, turbulent winds.
2. The tall towers and blades up to 90 m long are difficult to transport. Transportation can now cost 20 per cent of equipment costs.
3. Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.

4. Massive tower construction is required to support the heavy blades, gearbox, and generator.
5. Reflection on tall HAWTs may affect side lobs of radar installations creating signal clutter, although filtering can suppress it.
6. Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
7. Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).
8. HAWTs require an additional yaw control mechanism to turn the blades toward the wind.
9. In order to minimise fatigue loads due to wake turbulence, wind turbines are usually sited a distance of 5 rotor diameters away from each other, but the spacing depends on the manufacturer and the turbine model.

### *Vertical axis wind turbines*

Vertical axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. VAWTs can utilise winds from varying directions. With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque. Drag may be created when the blade rotates into the wind.

It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten the service life.

However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50 per cent of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

### Subtypes

*Darrieus wind turbine:* 'Eggbeater' turbines or Darrieus turbines, were named after the French inventor, Georges Darrieus. They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability. They also generally require some external power source or an additional Savonius rotor to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in greater solidity of the rotor. Solidity is measured by blade area divided by the rotor area. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.

*Giromill:* A subtype of Darrieus turbine with straight, as opposed to curved, blades. The cycloturbine variety has variable pitch to reduce the torque pulsation and is self-starting. The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a lower blade speed ratio; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses. Straight, V or curved blades may be used.

*Savonius wind turbine:* These are drag-type devices with two (or more) scoops that are used in anemometers, Flettner vents (commonly seen on bus and van roofs), and in some high-reliability low-efficiency power turbines. They are always self-starting if there are at least three scoops. They sometimes have long helical scoops to give a smooth torque.

### Advantages of vertical axis wind turbines

1. A massive tower structure is less frequently used, as VAWTs are more frequently mounted with the lower bearing mounted near the ground.
2. Designs without yaw mechanisms are possible with fixed pitch rotor designs.
3. The generator of a VAWT can be located nearer the ground, making it easier to maintain the moving parts.
4. VAWTs have lower wind start-up speeds than HAWTs. Typically, they start creating electricity at 6 mph (10 km/hr).
5. VAWTs may be built at locations where taller structures are prohibited.
6. VAWTs situated close to the ground can take advantage of locations where mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.
7. VAWTs may have a lower noise signature.

### *Disadvantages of vertical axis wind turbines*

1. A VAWT that uses guy-wires to hold it in place puts stress on the bottom bearing as all the weight of the rotor is on the bearing. Guy wires attached to the top bearing increase downward thrust in wind gusts. Solving this problem requires a superstructure to hold a top bearing in place to eliminate the downward thrusts of gust events in guy wired models.
2. The stress in each blade due to wind loading changes sign twice during each revolution as the apparent wind direction moves through 360 degrees. This reversal of the stress increases the likelihood of blade failure by fatigue.
3. While VAWTs' components are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts very difficult without dismantling the structure, if not designed properly.
4. Having rotors located close to the ground where wind speeds are lower due to the ground's surface drag, VAWTs may not produce as much energy at a given site as a HAWT with the same footprint or height.

## 8.10.2 Turbine design and construction

Wind turbines are designed to exploit the wind energy that exists at a location. Aerodynamic modelling is used to determine the optimum tower height, control systems, number of blades and blade shape. Wind turbines convert wind energy to electricity for distribution. Conventional horizontal axis turbines can be divided into three components.

1. The rotor component, which is approximately 20 per cent of the wind turbine cost, includes the blades for converting wind energy to low speed rotational energy.
2. The generator component, which is approximately 34 per cent of the wind turbine cost, includes the electrical generator, the control electronics, and most likely a gearbox (e.g. planetary gearbox, adjustable-speed drive or continuously variable transmission) component for converting the low speed incoming rotation to high speed rotation suitable for generating electricity.
3. The structural support component, which is approximately 15 per cent of the wind turbine cost, includes the tower and rotor yaw mechanism.

### 8.10.3 Small wind turbines

Small wind turbines may be as small as a fifty-watt generator for boat or caravan use. The US Department of Energy's National Renewable Energy Laboratory (NREL) defines small wind turbines as those smaller than or equal to 100 kW. Small units often have direct drive generators, direct current output, aeroelastic blades, lifetime bearings, and use a vane to point into the wind.

Larger, more costly turbines generally have geared power trains, alternating current output, flaps and are actively pointed into the wind. Direct drive generators and aeroelastic blades for large wind turbines are being researched.

### 8.10.4 Rotor

To increase the efficiency of wind turbines, rotor planning principles are very important for wind turbines with horizontal axis. It is not possible to expect the maximum efficiency from a wind turbine that is installed without doing the optimisation processes. At this point, rotor blades aerodynamic features are very important. It is necessary to put forward the power value that can be obtained from rotor blades. It is possible to conduct power tests indoors or under natural conditions. But in both methods, real rotor blades have to be produced. And this means cost. For this reason, first miniature blades can be produced and the tests can be conducted on these miniature rotor blades.

The main forces in atmosphere that produce wind and effect its speed is: pressure grading force, diverting force, centrifugal force and friction force. Pressure gradient force acts to move the air from high pressure to low pressure. Diverting force affects the air from two ways: one is as diverting force of earth's rotation for movements from the equator to poles or in the opposite direction. Winds, in general, are under the effect of a force that wants to divert them from their centre because they curl around a centre. This force is called centrifugal force. Friction force tries to decrease the speed of wind. The effect of this forces the greatest when near to earth's surface.

#### *Importance of rotor*

Rotor is the organ that transforms the kinetic energy of wind to mechanic energy. For this reason it is very important for wind turbines. It is very important for rotor and rotor blades to have optimum features, because these have a direct effect on the efficiency of wind turbines.

A flow mass has a kinetic energy because of its speed.

$$E = \frac{M}{2} V^2 \qquad \text{... (8.1)}$$

The achievement derives from the energy per time. Calculation of the mass flow:

$$m = \rho \cdot V \cdot A \qquad \text{... (8.2)}$$

Into these conditions we can compute the power with the following equation:

$$P = \frac{\rho}{2} . A . V^3 \qquad \text{... (8.3)}$$

Power equity gives the theoretic power that can be obtained from the kinetic energy that is stored in wind as Watt. This theoretic power has to be transformed into useful power by the help of turbine rotor. At this point a constant, which is effected by wind speed, turbine shaft speed and blade choice has to be taken into consideration. This constant is called ideal power constant (Cp). Blade types, blade form, inclination angle and speed of blade's tip are effective factors in here. In Fig. 8.6 the diagram of the ideals power coefficient. Theoretically ideal power constant cannot exceed 0.59. This constant is called Betz constant. In practice, this value is even smaller, because mechanical losses ($\eta$) come into effect in practice. But mechanic efficiency value can be neglected in calculations, because it is close to 1. Thus the equation can be written as below:

$$P = \frac{\rho}{2} . A . V^3 . C_p . \eta \qquad \text{... (8.4)}$$

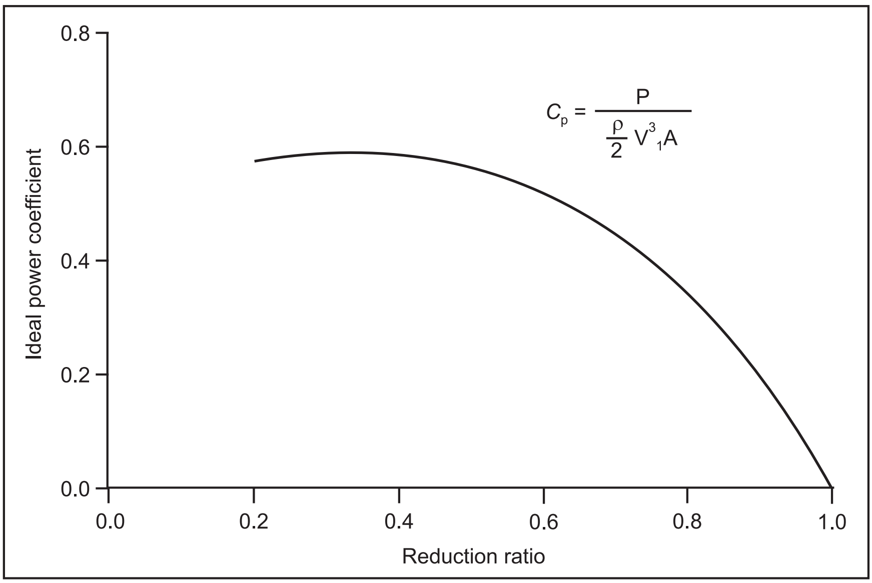



**Figure 8.6** Power coefficient (Cp) according to Betz

One thing that must not be forgotten in here is that air density is 1.225 kg $m^{-3}$ under standard meteorological conditions (temperature: 15°C and air pressure: 1013.3 hPa). The changes in air temperature and air pressure will change air density.

Obtaining maximum energy production from a wind turbine depends on various factors. These are factor like the height of wind turbine; wind turbine blade's sweep area and aerodynamic structure, air density and wind speed. The most important ones of these factors are the height of wind turbine and aerodynamic structure of wind turbine. The height of wind turbine is important because wind speed increases as we go away from earth's surface. Aerodynamic structure of wind turbine blade is important, because it can transform maximum 59 per cent of the kinetic energy that wind has to useful energy.

*Rotor aerodynamic of wind turbine:* In transformation of wind energy, which is formed by heating of different points of the atmosphere by the main energy source sun, to electric energy; wind rotor, which is the first ring in transformation chain, can be designed according to Betz or Glaubert–Schmitz for the purpose of transferring the existing wind power with minimum loss.

*Wind turbine rotor height:* As wind speed gets away from earth's surface, it frees itself from the friction effect cause by the roughness of earth's surface. Thus it moves more freely. As it gets away from obstacles that decelerate its speed, its speed increases. It is assumed that winds that are 1000 m above the earth's surface, namely geostrophic winds are not affected by the roughness of earth's surface and friction losses. At the light of these thoughts, we can say that there is a relation between wind speed and wind height. This is the reason why wind turbines are built as high as possible.

*Wind turbine rotor diameter:* Besides determining turbine height, the diameter of the wind that rotor blade sweeps has to be determined. The diameter of the wind that rotor blade sweeps has a direct effect on the power that will obtained from turbine.

*The wind potential in where the wind turbine rotor will operate:* Wind potential in where the wind turbine will installed is very important. For this reason it is one of the parameters that have to be considered in rotor design. Wind speed potential in where the wind turbine will installed has to be observed at least for 6 months. Wind potentials is directly effective on the efficiency of the wind turbine rotor. Wind speed is the most important factor about the energy of the wind. The power that will be obtained from wind is directly proportional to wind speed's third power.

When wind speed has this much effect on the power that will be obtained from the wind turbine, the wind potential in where the turbine will be built is very important. The main objective is to find the point where the wind speed is maximum and install the turbine there.

*Land structure of the place where the wind turbine rotor will operate:* There is a relation between wind speed and wind height. This relation is dependent on some conditions. These conditions originate from land shapes. Same conditions do not apply in a flat land surface and surface with obstacles. In a flat land surface as height increases, speed also increase in a direct ratio, but his will not be true in a land surface with obstacles. In a surface with obstacles, wind will have to climb over obstacles to resume its course and this will cause a pause in wind's speed.

If the most important criteria for obtaining energy from wind are wind speed, then it is very important to find the areas where wind speed is high and install wind turbine rotor there. But we don't have to make a false assumption that when we increase the height we will always catch winds that contain more energy. The factors that wind speed is affect depending on height are: Von Karman constant, surface friction speed and roughness length.

*The performance demanded from wind turbine rotor:* Before choosing a wind turbine for an enterprise, first we have to determine how much electric power our enterprise needs. This way, power of the wind turbine that will be installed can be determined. The performance demanded from the rotor has to be determined according to the enterprise's installed power.

To increase the efficiency of wind turbines, rotor planning principles are very important for wind turbines with horizontal axis. It is not possible to expect the maximum efficiency from a wind turbine that is installed without doing the optimisation processes.

Like in every topic, to be successful when making use of wind energy, basic values must be based on scientific data. When the topic is considered from this point of view, rotor design parameters have to be put forward in wind turbines. Starting from here, the most suitable systems can be developed by taking source data as a basis. The basic strategy is to put into practice high performance systems that can compete.

## 8.11 Wind electricity basics

Small wind-electric systems can provide electricity on remote, off-grid sites or right in town connected to the utility grid. Although wind systems require more maintenance and need more attention than solar-electric or microhydro-electric systems, if you invest up front in good equipment, design, and installation, wind-electric systems can make economic and environmental sense. They also bring a great deal of satisfaction—there's nothing quite like watching your wind generator convert a summer breeze or a winter storm into electrical energy.

Boiled down to its simplest principles, a wind generator's rotating blades convert the wind's kinetic energy into rotational momentum in a shaft. The rotating shaft turns an alternator, which makes electricity. This electricity is transmitted through wiring down the tower to its end use.

The blades use engineered airfoils, matched to the alternator, that capture the wind's energy. Most modern wind generators use three blades, the best compromise between the highest efficiency possible (one blade) and the balance that comes with multiple blades. Together, the blades and the hub they are attached to are termed the rotor, which is the collector of the system, intercepting winds that pass by. Most turbines on the market today are upwind machines—their blades are on the windward side of the tower. A few downwind machines are available, but neither configuration has a clear performance advantage over the other.

In most small-scale designs, the rotor is connected directly to the shaft of a permanent magnet alternator, which creates wild, three-phase AC. Wild, three-phase electricity means that the voltage and frequency vary continuously with the wind speed. They are not fixed like the 60 Hz and 120 VAC electricity coming out of common household outlets. The wild output is rectified to DC to either charge batteries or feed a grid-synchronous inverter. In most designs (up to 15 kW in peak capacity), the rotor is usually connected directly to the alternator, which eliminates the additional maintenance of gears. In systems 20 kW and larger, as well as some smaller wind systems (like the Endurance, Tulipo or Aircon), a gearbox is used to increase alternator speed from a slower turning rotor.

The blades must turn to face the wind, so a yaw bearing is needed, allowing the wind turbine to track the winds as they shift direction. The tail directs the rotor into the wind. Some sort of governing system limits the rotor rpm as well as generator output to protect the turbine from high winds. A shutdown mechanism is also useful to stop the machine when necessary, such as during an extreme storm, when you do not need the energy or when you want to service the system.

*How wind turbines are rated:* Wind turbine rating is a tricky affair. While solar-electric module or microhydro-electric turbine production can be predicted fairly realistically based on rated output, this number is very misleading with wind turbines. Why? Because rated output is pegged to a particular wind speed, and different manufacturers use different wind speeds to determine rated output. Also, the power available in the wind varies with the cube of its speed, so small increases in wind speed result in large increases in power available to the rotor. A 10 per cent increase in wind speed yields a 33 per cent increase in power available in the wind. Conversely, this means that a turbine rated at 1000 watts at 28 mph might produce only 125 watts or less at half that wind speed, 14 mph.

So what's a wind turbine buyer to do? Ignore the peak output and the power curve. Look for the monthly or annual energy numbers for the turbine, estimated for the average wind speed you expect or measure at your site. These will be given in kWh per month (or year) in the manufacturer's specifications for each turbine. Energy is what you are after, not peak power. If, for example, you are looking for a turbine that can produce 300 kWh per month, and you know that you have a 10 mph average wind speed at the proposed turbine height, you can shop for a turbine that is predicted to generate that much energy in that average wind speed.

If you can not get energy production estimates from the manufacturer or a turbine owner, look for a different manufacturer. This is basic information that any manufacturer should supply. However, knowing a turbine's swept area may also help you calculate the annual energy output for the wind turbine. All other things being equal, 'there is no replacement for displacement'.

A turbine's revolutions per minute (rpm) at its rated wind speed can give you some idea of the relative aerodynamic sound of the machine, and also speaks to longevity. Slower-turning wind turbines tend to be quieter and last longer. High rpm machines wear out components, such as bearings, much faster. In addition, the faster blades move through the air, the greater the possibility that they will waste some of that energy as sound from the blades.

*How to choose a wind turbine:* Trying to keep an inexpensive wind generator running can be an uphill battle that you'll soon tire of. But expect to pay more for a better machine—it is a tough job to design and manufacture a long-lasting, small-scale wind generator.

*The bottom line:* Buy a turbine that has a very good track record and a good warranty—five years is preferable but not always available in the small wind industry. A warranty is one indication of the manufacturer's confidence in their product, and their intention to stand behind it.

Real-world reports from users carry even more weight than a warranty, so search for people who own the model of turbine you are considering buying, and get the straight scoop from them about performance, durability, reliability, and maintenance issues.

Some manufacturers make only battery-charging machines, and may offer a variety of turbine voltages. Others produce machines intended to connect to grid-synchronous inverters without batteries. One machine even includes an inverter integrated with the turbine itself. Make sure you are buying a machine that is appropriate for your intended use.

When you look at prices, keep in mind that just buying a wind turbine will not get you any wind-generated electricity. You will also need most or all of the components mentioned elsewhere; also budget for equipment rental, like a backhoe and crane, concrete and rebar, electrical components, shipping, and sales tax. Unless you do all of the work yourself, also factor in installation labour expenses. These costs can add up significantly, so make sure that you research and understand all of the associated expenses before committing to a purchase. Many people are quite surprised to learn that the wind turbine cost can range from only 10 per cent to as much as 40 per cent of the entire wind system's expenses. Small-scale wind energy is not for the half-hearted, uninvolved or uncommitted, and probably not for folks who never change the oil in their vehicles (or are willing to spend the bucks to hire someone to do the tower work).

## 8.12 Wind-electric system types

### 8.12.1 Off-grid wind-electric systems

Off-grid wind-electric systems are battery based. People generally choose these systems because their home or other energy use is not connected to the grid, and connection would be expensive. Others prefer the independence of off-grid systems or live where utilities and governments make it difficult to tie a renewable energy system to the grid.

Off-grid systems are limited in capacity by the size of the generating sources (wind turbine, solar-electric array, fuel-fired generator, etc.), the resources available, and the battery bank size. Off-grid homeowners have to learn to live within the limitations of their system capacity (Fig. 8.7).

### 8.12.2 Grid-tied wind-electric system with battery backup

Connecting a wind-electric system to the utility grid with battery backup gives you the best of both worlds. You have the unlimited capacity of the grid at your disposal, and you can send your surplus wind energy to the grid. When the grid is down, you can still use your system, within the limitations of the battery bank and turbine. Wind-electric systems can be a much better match for utility backup than solar-electric systems, since many grid outages are caused by high winds. The drawback is that this is the most expensive type of wind-electric system you can install (Fig. 8.8).

### 8.12.3 Battery-less grid-tied wind-electric system

Connecting to the grid without batteries is the most cost-effective and environmentally friendly way to go. You eliminate batteries, which are costly, require maintenance, and carry a significant efficiency penalty. The only drawback of battery-less systems is that when the grid is down, your system shuts down. But in most grid-serviced areas, utility outages are only a few hours a year—a small inconvenience to endure for the efficiency, environmental friendliness, and thriftiness of these systems. Battery-less grid-tie systems may see increased performance (sometimes dramatically) from the wind turbine compared to battery-based systems.

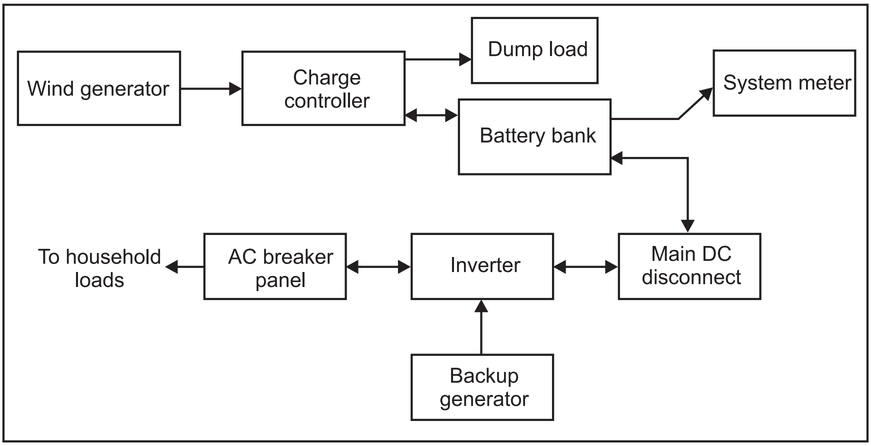



**Figure 8.7** Off-grid wind-electric system

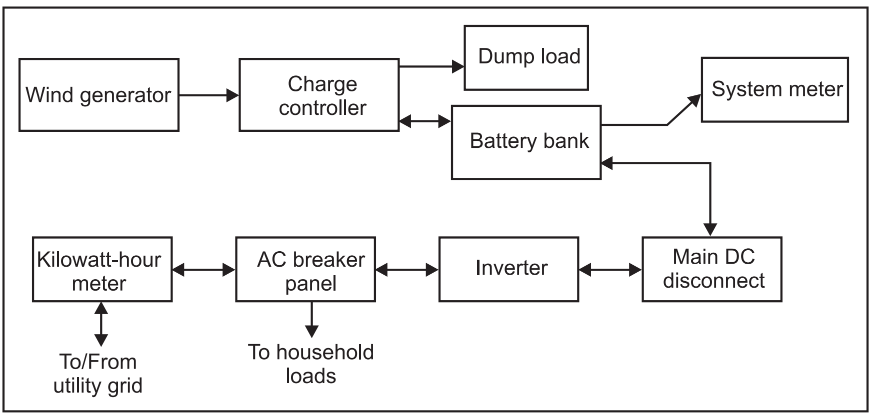



**Figure 8.8** Grid-tied wind-electric system with battery backup

This is because the inverter's electronics can match the wind's load more exactly, running the turbine at optimum speed, and extracting the maximum energy (Fig. 8.9).

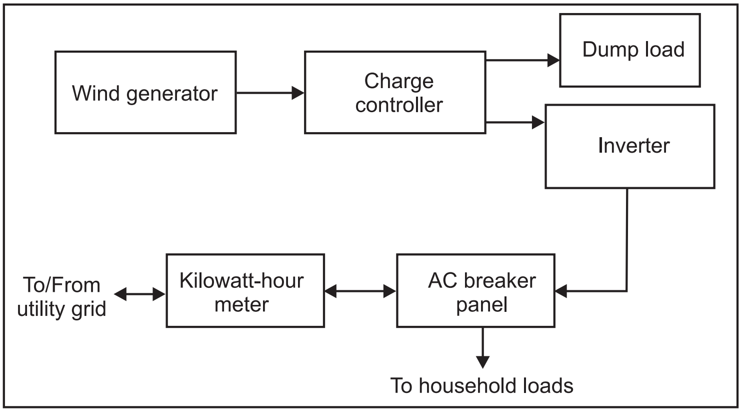



**Figure 8.9** Battery-less grid-tied wind-electric system

## 8.12.4 Direct-drive battery-less wind-electric system

These are the least common wind-electric systems, typically used for water pumping. A turbine is matched to a pump, often through an electronic controller. When the wind blows, water is pumped to an elevated tank, a stock-watering tank or directly to the land to irrigate. These systems can be simple and cost effective in the right situation. Direct-drive systems are also used for heating, which can be a good match, since it's normally colder when it's windy. But heating is a big load, so large turbines are needed (Fig. 8.10).

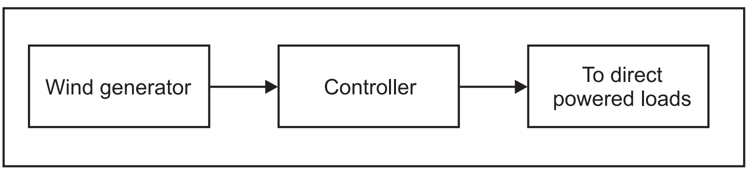



**Figure 8.10** Direct-drive battery-less wind-electric system

## 8.12.5 Wind-electric system components

Here are some brief descriptions of the common equipment used in grid-intertied and off-grid wind-electric systems. Systems vary—not all equipments are necessary for every system type.

1. Wind generator
2. Tower
3. Brake
4. Charge controller

5. Dump load
6. Battery bank
7. System meter
8. Main DC disconnect
9. Inverter
10. AC breaker panel
11. Kilowatt-hour meter
12. Backup generator

### *Wind generator*

The wind generator is what actually generates electricity in the system. Most modern wind generators are upwind designs (blades are on the side of the tower that faces into the wind), and couple permanent magnet alternators directly to the rotor (blades). Three-bladed wind generators are most common, providing a good compromise between efficiency and rotor balance.

Small wind turbines protect themselves from high winds (governing) by tilting the rotor up or to the side or by changing the pitch of the blades. Electricity is transmitted down the tower on wires, most often as three-phase wild alternating current (AC). It is called ‘wild’ because the voltage and frequency vary with the rotational speed of the wind turbine. The output is then rectified to direct current (DC) to charge batteries or to be inverted for grid connection.

### *Tower*

A wind generator tower is very often more expensive than the turbine. The tower puts the turbine up in the ‘fuel’—the smooth strong winds that give the most energy. Wind turbines should be sited at least 30 ft (9 m) higher than anything within 500 ft (152 m).

Three common types of towers are tilt-up, fixed-guyed, and freestanding. Towers must be specifically engineered for the lateral thrust and weight of the turbine, and should be adequately grounded to protect your equipment against lightning damage.

### *Brake*

Most wind turbines have some means of stopping the turbine for repairs, in an emergency, for routine maintenance, or when the energy is not needed. Many turbines have ‘dynamic braking’, which simply shorts out the three electrical phases and acts as a disconnect. Others have mechanical braking, either via a disc or drum brake, activated by a small winch at the base of the tower. Still others have mechanical furling, which swings the rotor out of the wind. Mechanical braking is usually more effective and reliable than dynamic braking.

## *Charge controller*

A wind-electric charge controller's primary function is to protect your battery bank from overcharging. It does this by monitoring the battery bank—when the bank is fully charged, the controller sends energy from the battery bank to a dump (diversion) load.

Many wind-electric charge controllers are built into the same box as the rectifiers (AC-to-DC converters). Overcurrent protection is needed between the battery and controller/dump load.

In battery-less grid-tie systems, there is no controller in normal operation, since the inverter is selling whatever energy the turbine is generating. But there will be some control function in the case of grid failure, and there may be electronics before the inverter to regulate the input voltage.

## *Dump load*

Solar-electric modules can be turned off—open circuited—with no damage. Most wind generators should not run unloaded. They will run too fast and too loud, and may self-destruct. They must be connected to a battery bank or load. So normally, a charge controller that has the capability of being a diversion controller is used. A diversion controller takes surplus energy from the battery bank and sends it to a dump load. In contrast, a series controller (commonly used in PV systems), actually opens the circuit.

A dump load is an electrical resistance heater, and it must be sized to handle the full generating capacity of the wind generator used. These dump loads can be air or water heaters, and are activated by the charge controller whenever the batteries or the grid cannot accept the energy being produced.

## *Battery bank*

Your wind generator will produce electricity whenever the wind blows above the cut-in speed. If your system is off-grid, you'll need a battery bank—a group of batteries wired together—to store energy so you can have electricity when it is not windy. For off-grid systems, battery banks are typically sized to keep household electricity running for one to three calm days. Grid-intertied systems also can include battery banks to provide emergency backup during blackouts—perfect for keeping critical electric loads operating until the grid is up again.

Use only deep-cycle batteries in wind-electric systems. Lead-acid batteries are the most common battery type. Flooded lead-acid batteries are usually the least expensive, but require adding distilled water occasionally to replenish water lost during the normal charging process. Sealed absorbent glass mat (AGM) batteries are maintenance free and designed for grid-tied systems where the batteries are typically kept at a full state of charge. Sealed gel-cell batteries can be a good choice to use in unheated spaces due to their freeze-resistant qualities.

### *System meter*

System meters can measure and display several different aspects of your wind-electric systems performance and status—tracking how full your battery bank is, how much electricity your wind generator is producing or has produced, and how much electricity is in use. Operating your system without metering is like running your car without any gauges—although possible to do, it is always better to know how much fuel is in the tank.

### *Main DC disconnect*

In battery-based systems, a disconnect between the batteries and inverter is required. This disconnect is typically a large, DC-rated breaker mounted in a metal enclosure. This breaker allows the inverter to be quickly disconnected from the batteries for service, and protects the inverter-to-battery wiring against electrical fires.

### *Inverter*

Inverters transform the electricity produced by your wind generator into the AC electricity commonly used in most homes for powering lights and appliances. Grid-tied inverters synchronise the electricity they produce with the grid's 'utility grade' AC electricity, allowing the system to feed wind electricity to the utility grid.

Grid-tie inverters are either designed to operate with or without batteries. Battery-based inverters for off-grid or grid-tie systems often include a battery charger, which is capable of charging a battery bank from either the grid or a backup generator during cloudy weather.

### *AC breaker panel*

The AC breaker panel is the point at which all of a home's electrical wiring meets with the provider of the electricity, whether that is the grid or a solar-

electric system. This wall-mounted panel or box is usually installed in a utility room, basement, garage or on the exterior of the building. It contains a number of labelled circuit breakers that route electricity to the various rooms throughout a house. These breakers allow electricity to be disconnected for servicing, and also protect the building's wiring against electrical fires.
Just like the electrical circuits in your home or office, an inverter's electrical output needs to be routed through an AC circuit breaker. This breaker is usually mounted inside the building's mains panel, which enables the inverter to be disconnected from either the grid or from electrical loads if servicing is necessary, and also safeguards the circuit's electrical wiring.

### *Kilowatt-hour meter*

Most homes with a grid-tied wind-electric system will have AC electricity both coming from and going to the electric utility grid. A bidirectional kWh meter can simultaneously keep track of how much electricity you are using and how much your system is producing. The utility company often provides intertie-capable meters at no cost.

### *Backup generator*

Off-grid wind-electric systems can be sized to provide electricity during calm periods when the wind doesn't blow. But sizing a system to cover a worst-case scenario, like several calm weeks during the summer, can result in a very large, expensive system that will rarely get used to its capacity and will run a huge surplus in windy times. To spare your pocketbook, go with at least two sources of energy. Wind-PV hybrid systems are often an excellent fit with local renewable resources. But a backup, fuel-powered generator still may be necessary.

Engine-generators can be fuelled with biodiesel, petroleum diesel, gasoline or propane, depending on the design. Most generators produce AC electricity that a battery charger (either stand-alone or incorporated into an inverter) converts to DC energy, which is stored in batteries. Like most internal combustion engines, generators tend to be loud and stinky, but a well-designed renewable energy system will require running them only 50 to 200 hours a year or less.

## 8.13 Wind farm

A wind farm is a group of wind turbines in the same location used for production of electric power. Individual turbines are interconnected with a

medium voltage power collection system and communications network. At a substation, this medium voltage electrical current is increased in voltage with a transformer for connection to the high voltage transmission system. Near shore turbine installations are on land within 5 miles of a shoreline or on water within ten miles. These areas are good sites for turbine installation, because of wind produced by convection due to differential heating of land and sea each day. Wind speeds in these zones share the characteristics of both onshore and offshore wind, depending on the prevailing wind direction (Fig. 8.11).
Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise is mitigated by distance. Because water has less surface roughness than land (especially deeper water), the average wind speed is usually considerably higher over open water.

Spain, Denmark, and Germany are Europe's main wind energy producers. A large wind farm may consist of a few dozen to several hundred individual wind turbines, and cover an extended area of hundreds of square miles, but the land between the turbines may be used for agricultural or other purposes. A wind farm may be located offshore to take advantage of strong winds blowing over the surface of an ocean or lake. The United States is behind in developing sea-based wind farms for many reasons: economic and regulatory uncertainties, local opposition (not in my backyard), and even the relative bounty of cheaper land-based wind power resources have all conspired to slow any drive to develop wind power resources on the sea.

**Figure 8.11** Wind farm in England

## 8.13.1 Location planning

A quantity called the wind power density (WPD) is used to select locations for wind energy development. The WPD is a calculation relating to the effective force of the wind at a particular location, frequently expressed in term of the elevation above ground level over a period of time. It takes into account velocity and mass. Colour coded maps are prepared for a particular area describing, for example, ‘Mean Annual Power Density, at 50 m’. The results of the above calculation are used in an index developed by the National Renewable Energy Lab and referred to as ‘NREL CLASS’. The larger the WPD calculation the higher it is rated by class.

Wind farm citing can be highly controversial, particularly when sites are picturesque or environmentally sensitive, such as having substantial bird life or requiring roads to be built through pristine areas. These areas are generally non-residential due to the noise concerns and setback requirements. Access to the power grid must be taken into mind. The further from the power grid, there will be need for more transmission lines to span from the farm directly to the power grid or transformers will have to be built on the premises depending upon the types of turbines being used.

### *Wind speed*

As a general rule, wind generators are practical if wind speed is 10 mph (16 km/hr or 4.5 m/s) or greater. An ideal location would have a near constant flow of non-turbulent wind throughout the year with a minimum likelihood of sudden powerful bursts of wind. An important factor of turbine citing is also access to local demand or transmission capacity. Usually sites are preselected on basis of a wind atlas, and validated with wind measurements. Meteorological wind data alone is usually not sufficient for accurate citing of a large wind power project. Collection of site specific data for wind speed and direction is crucial to determining site potential. Local winds are often monitored for a year or more, and detailed wind maps constructed before wind generators are installed. To collect wind data a meteorological tower is installed with instruments at various heights along the tower. All towers include anemometers to determine the wind speed and wind vanes to determine the direction. The towers generally vary in height from 30 to 60 m. The towers primarily are guyed steel-pipe structures which are left to collect data for one to two years and then disassembled. Data is collected by a data logging device which stores and transmits data for analysis. Great attention must be paid to the exact positions of the turbines (a process known as micro-citing) because a difference of 30 m can nearly double energy production. For smaller installations where such data collection is too expensive or time consuming, the normal way of prospecting for wind-power sites is to directly look for trees or vegetation that are permanently 'cast' or deformed by the prevailing winds. Another way is to use a wind-speed survey map or historical data from a nearby meteorological station, although these methods are less reliable.

## *Altitude*

The wind blows faster at higher altitudes because of the reduced influence of drag. The increase in velocity with altitude is most dramatic near the surface and is affected by topography, surface roughness, and upwind obstacles such as trees or buildings. Typically, the increase of wind speeds with increasing height follows a wind profile power law, which predicts that wind speed rises proportionally to the seventh root of altitude. Doubling the altitude of a turbine, then, increases the expected wind speeds by 10 per cent and the expected power by 34 per cent.

## *Wind park effect*

The 'wind park effect' refers to the loss of output due to mutual interference between turbines. Wind farms have many turbines and each extracts some of the energy of the wind. Where land area is sufficient, turbines are spaced three to five rotor diameters apart perpendicular to the prevailing wind, and five to ten rotor diameters apart in the direction of the prevailing wind, to minimise efficiency loss. The loss can be as low as 2 per cent of the combined nameplate rating of the turbines.

In a large wind park, due to 'multifractal' effects between individual rotors, the behaviour deviates significantly from Kolmogorov's turbulence scaling for individual turbines.

## *Environmental and aesthetic impacts*

Compared to the environmental effects of traditional energy sources, the environmental effects of wind power are relatively minor. Wind power consumes no fuel, and emits no air pollution, unlike fossil fuel power sources. The energy consumed to manufacture and transport the materials used to build a wind power plant is equal to the new energy produced by the plant within a few months of operation.

Danger to birds and bats has been a concern in many locations. Some dismiss the number of birds killed by wind turbines as negligible when compared to the number that die as a result of other human activities, and

especially the environmental impacts of using non-clean power sources.
Effect on power grid

Utility-scale wind farms must have access to transmission lines to transport energy. The wind farm developer may be obligated to install extra equipment or control systems in the wind farm to meet the technical standards set by the operator of a transmission line. The company or person that develops the wind farm can then sell the power on the grid through the transmission lines and ultimately chooses whether to hold on to the rights or sell the farm or parts of it to big business like GE, for example.

## 8.13.2 Types

### *Onshore*

Onshore turbine installations in hilly or mountainous regions tend to be on ridgelines generally 3 km or more inland from the nearest shoreline. This is done to exploit the so-called topographic acceleration as the wind accelerates over a ridge. The additional wind speeds gained in this way make a significant difference to the amount of energy that is produced. Great attention must be paid to the exact positions of the turbines (a process known as micro-citing) because a difference of 30 m can sometimes mean a doubling in output.

### *Nearshore*

Nearshore turbine installations are on land within 3 km of a shoreline or on water within 10 km of land. These areas are good sites for turbine installation, because of wind produced by convection due to differential heating of land and sea each day. Wind speeds in these zones share the characteristics of both onshore and offshore wind, depending on the prevailing wind direction.

### *Offshore*

Offshore wind development zones are generally considered to be 10 km or more from land. Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise is mitigated by distance. Because water has less surface roughness than land (especially deeper water), the average wind speed is usually considerably higher over open water. Capacity factors (utilisation rates) are considerably higher than for onshore and nearshore locations.

Transporting large wind turbine components (tower sections, nacelles, and blades) is much easier over water than on land, because ships and barges can handle large loads more easily than trucks/lorries or trains. On land, large goods vehicles must negotiate bends on roadways, which fixes the maximum length of a wind turbine blade that can move from point to point on the road network; no such limitation exists for transport on open water. Offshore wind turbines will probably continue to be the largest turbines in operation, since the high fixed costs of the installation are spread over more energy production, reducing the average cost.

Turbine components (rotor blades, tower sections) can be transported by barge, making large parts easier to transport offshore than on land, where turn clearances and underpass clearances of available roads limit the size of turbine components that can be moved by truck. Similarly, large construction cranes are difficult to move to remote wind farms on land, but crane vessels easily move over water. Offshore wind farms tend to be quite large, often involving over 100 turbines.

## 8.14 Environmental impact of wind power

Compared to the environmental impact of traditional energy sources, the environmental impact of wind power is relatively minor. Wind power consumes no fuel, and emits no air pollution, unlike fossil fuel power sources. The energy consumed to manufacture and transport the materials used to build a wind power plant is equal to the new energy produced by the plant within a few months. While a wind farm may cover a large area of land, many land uses such as agriculture are compatible, with only small areas of turbine foundations and infrastructure made unavailable for use.

There are reports of bird and bat mortality at wind turbines as there are around other artificial structures. The scale of the ecological impact may or may not be significant, depending on specific circumstances. Prevention and mitigation of wildlife fatalities, and protection of peat bogs, affect the citing and operation of wind turbines. There are anecdotal reports of negative effects from noise on people who live very close to wind turbines.

### 8.14.1 Carbon dioxide emissions and pollution

Wind power consumes no fuel and no water for continuing operation, and has no emissions directly related to electricity production. Wind turbines produce no carbon dioxide, sulphur dioxide, mercury, particulates or any other type of air pollution, unlike fossil fuel power sources. Wind power plants consume resources in manufacturing and construction. During manufacture of the wind turbine, steel, concrete, aluminium and other materials will have to be made and transported using energy-intensive processes, generally using fossil energy sources.

The wind turbine manufacturer Vestas states that initial carbon dioxide emissions 'pay back' is within about 9 months of operation for offshore turbines.

## 8.14.2 Ecology

### *Land use*

Wind farms are often built on land that has already been impacted by land clearing. The vegetation clearing and ground disturbance required for wind farms is minimal compared with coal mines and coal-fired power stations. If wind farms are decommissioned, the landscape can be returned to its previous condition, although the concrete foundations will be left in place and access tracks may also be retained.

### *Impact on wildlife*

Environmental assessments are routinely carried out for wind farm proposals, and potential impacts on the local environment (e.g. plants, animals, soils) are evaluated. Turbine locations and operations are often modified as part of the approval process to avoid or minimise impacts on threatened species and their habitats. Any unavoidable impacts can be offset with conservation improvements of similar ecosystems which are unaffected by the proposal.

### *Birds*

A study estimates that wind farms are responsible for 0.3 to 0.4 fatalities per gigawatt-hour (GWh) of electricity while fossil-fuelled power stations are responsible for about 5.2 fatalities per GWh. The study therefore states that fossil fuel based electricity causes about 10 times more fatalities than wind farm based electricity, primarily due to habitat alteration from pollution and mountain-top removal for coal mining.

### *Bats*

Bats may be injured by direct impact with turbine blades, towers or transmission lines. Recent research shows that bats may also be killed when suddenly passing through a low air pressure region surrounding the turbine blade tips. The numbers of bats killed by existing onshore and near-shore facilities has troubled bat enthusiasts. Migratory bat species appear to be particularly at risk, especially during key movement periods (spring and more importantly in fall).

### *Climate change*

Wind farms may affect weather in their immediate vicinity. Spinning wind turbine rotors generate a lot of turbulence in their wakes like the wake of a boat. This turbulence increases vertical mixing of heat and water vapour that affects the meteorological conditions downwind.

### 8.14.3 Impact on people

#### *Safety*

Operation of any utility-scale energy conversion system presents safety hazards. Wind turbines do not consume fuel or produce pollution during normal operation, but still have hazards associated with their construction, operation and maintenance.

With the installation of industrial sized wind turbines numbering in the thousands, there have been at least 40 fatalities of workers due to the construction, operation, and maintenance of wind turbines, and other injuries and deaths attributed to the wind power life-cycle. Most worker deaths involve falls or becoming caught in machinery while performing maintenance inside turbine housings.

#### *Aesthetics*

Newer wind farms have larger, more widely spaced turbines, and have a less cluttered appearance than older installations. Wind farms are often built on land that has already been impacted by land clearing and they coexist easily with other land uses (e.g. grazing, crops). They have a smaller footprint than other forms of energy generation such as coal and gas plants. Wind farms may be close to scenic or otherwise undeveloped areas, and aesthetic issues are important for onshore and near-shore locations.

Aesthetic issues are subjective and some people find wind farms pleasant and optimistic or symbols of energy independence and local prosperity. While some tourism officials predict wind farms will damage tourism, some wind farms have themselves become tourist attractions, with several having visitor centres at ground level or even observation decks atop turbine towers.

#### *Noise*

Modern wind turbines produce significantly less noise than older designs. Turbine designers work to minimise noise, as noise reflects lost energy and output. Noise levels at nearby residences may be managed through the citing of turbines, the approvals process for wind farms, and operational management of the wind farm. Renewable UK, a wind energy trade organisation, has said that the noise measured 350 m from a wind farm is less than that from normal road traffic or in an office; some physicians and acoustic engineers have reported problems from wind turbine noise, including sleep deprivation, headaches, dizziness, anxiety and vertigo.

# 9
# Status of wind energy in India

## 9.1 Introduction

Nearly two decades ago the Indian economy was snatched back from the brink of a composite economic crisis. The Indian government undertook some hard-hitting liberalisation measures that would have been unthinkable in a business as usual political landscape. Largely as a result of those actions, today India is in a position to be counted as one of the 'emerging economies'.

Successive governments have looked towards locking in an average economic growth rate of at least 6–8 per cent, up from 3.5 per cent from the 1950s through the 1980s. The original objective of the 11th Five-year plan (2007–2012) was to achieve a GDP growth rate of 9 per cent over this period. This was revised to 8.1 per cent last year by the planning commission. Given the plans for rapid economic growth, the requirement for energy services and supporting infrastructure is simultaneously escalating.

Electricity demand has continuously outstripped production, and a peak energy shortage of around 12.7 per cent prevailed in 2009–10. To meet this shortfall as well as the National Electricity Policy target of 'Electricity for All by 2012', the cleanest options available to India are Renewable Energy Technologies (RETs). For the government to seriously consider meeting its promise of electricity for all by 2012, renewable energy options including wind power will have to play a crucial role in India's emerging energy mix. Not only are they environmentally sound but also their project gestation periods are significantly shorter than those for thermal or nuclear power plants.

According to the Ministry of New and Renewable Energy (MNRE), today the share of renewable based capacity is 10.9 per cent (excluding large hydro) of the total installed capacity of 170 GW in the country, up from 2 per cent at the start of the 10th plan period (2002–2007). This includes 13,065.78 MW of wind, 2939 MW of small hydro power, 1562 MW of (bagasse based) cogeneration, 997 MW of biomass, 73.46 MW of 'waste to power' and 17.80 MW of solar PV for grid connected renewables at the end of 2010.

The originally stated cumulative target for the current plan period was to add 92 GW of new capacity of which about 14 GW was to come from renewable sources. Given the right mix of regulatory and institutional support, renewable sources could meet the proposed capacity addition of 14 GW from renewable energy before the end of the 11th five-year plan period (2007–2012). This would bring the total share of renewable energy sources up to 15 per cent of the new installed capacity in the 11th plan period.

Over the next decade, India will have to invest in options that not only provide energy security but also provide cost-effective tools for eradicating energy poverty across the board. India is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) and has as part of its obligations released a National Action Plan on Climate Change (released in June 2008) by Prime Minister Manmohan Singh which has laid out his government's vision for a sustainable and green future for India's economy. India's developmental needs will be challenged by climate change impacts. This requires a timely pre-emptive shift towards achieving an energy efficient and green economy. Over the next couple of decades renewable energy will play a major role in delivering that shift.

## 9.2 Wind power scenarios

There are several published scenarios that examine the future role of wind power globally as a part of the necessary energy system overhaul towards a clean energy future. The Global Wind Energy Council (GWEC) developed its scenarios in collaboration with Greenpeace international and the German Aerospace Centre (DLR). These scenarios are updated biennially. The resultant publication—the Global Wind Energy Outlook (GWEO)—first looks toward 2020, and then onwards to 2030 and 2050. Some of the other prominent scenarios are the World Energy Outlook (2010) from the International Energy Agency (IEA) and the Energy [R]evolution: A Sustainable World Energy Outlook by Greenpeace (2010).

There are many variables that will determine the path of development and growth of wind energy. Table 9.1 lists the assumptions underlying the GWEO scenarios and associated assumptions for wind power development.

## 9.3 GWEO scenario results

The GWEO scenarios show that even with the continuation of current policy measures to encourage wind power development and serious government efforts to meet existing targets, the resulting ‘Moderate’ scenario growth will put the development of wind power on a dramatically different trajectory from the IEA-based ‘Reference’ scenario. Table 9.2 lists the global cumulative wind power capacity.

The global wind markets have grown by an average 28 per cent per year in terms of total installed capacity during the last decade. The IEA’s Reference scenario suggests that growth rates for wind power would decrease substantially in the coming years, and that 2013 would see an addition of only 26.8 GW. However, in reality the global wind industry added 35.8 GW during the year. Table 9.3 lists the cumulative wind power capacity of India.

**Table 9.1** Global wind energy outlook: scenario and assumptions.

| Reference scenario (IEA based) | Moderate scenario | Advanced scenario |
|---|---|---|
| The most conservative of all, the‘reference’ scenario is based on the projections in the 2009 World Energy extent to which this industry could outlook from the IEA. This takes into account only existing policies and measures, but includes assumptions such as continuing electricity and gas market reform, the liberalisation of cross-border energy trade and recent policies aimed at combating pollution. The IEA’s figures only go out to the year 2030, but based on these assumptions, DLR has extrapolated both the overall reference scenario and the growth of wind power up to 2050. | The ‘Moderate’ scenario takes into account all policy and measures to already enacted or in planning stages around the world. It also assumes that the targets set by many countries for either renewable, emission reductions and/or wind energy are successfully implemented, as well as the modest implementation of new policies aimed at reducing pollution and carbon emissions. It also takes into account environmental and energy policy measures that were part of many governments economic stimulus packages implemented since late 2008. Up to 2014 the figures for installed capacity are closer to being forecasts than scenarios. | The most ambitious scenario, the ‘advanced’ version examines the support renewable energy either grow in a best case ‘wind energy vision’. The assumption here is a clear and unambiguous commitment to renewable energy as per the industry’s recommendations along with the political will necessary to carry it forward. |

**Table 9.2** Global cumulative wind power capacity (MW).

| Scenario | 2007 | 2008 | 2009 | 2010 | 2015 | 2020 | 2030 |
|---|---|---|---|---|---|---|---|
| Reference | 93,864 | 1,20,297 | 1,58,505 | 1,85,258 | 2,95,783 | 4,15,433 | 5,72,733 |
| Moderate | 93,864 | 1,20,297 | 1,58,505 | 1,98,717 | 4,60,364 | 8,32,251 | 17,77,550 |
| Advanced | 93,864 | 1,20,297 | 1,58,505 | 2,01,657 | 5,33,233 | 10,71,415 | 23,41,984 |

**Table 9.3** India: cumulative wind power capacity (MW).

| Year | Reference | Moderate | Advanced |
|---|---|---|---|
| 2009 | 10,926 | 10,926 | 10,926 |
| 2010 | 12,276 | 12,629 | 12,833 |
| 2015 | 19,026 | 24,747 | 29,151 |
| 2020 | 24,026 | 46,104 | 65,181 |
| 2030 | 30,526 | 1,08,079 | 1,60,741 |

The Indian market grew by almost 68 per cent on a year-on-year basis with 2139 MW of new capacity installed between January and December 2010. This made India the third largest annual market after China and the USA for 2010. With more than 13 GW of total installed capacity at the end of 2010, India ranks fifth in the world in terms of cumulative installed capacity. The IEA projects that 327 GW of power generation capacity will be needed in India by 2020, which would imply a yearly addition of about 16 GW. This is reflected in the stated target for new capacity addition by the Indian government under its 11th Five-Year Plan. The plan envisages an addition of 78.7 GW by 2012 from traditional sources (coal, nuclear and large hydro) and an additional 9 GW by 2013 (revised from 10.5 GW) from new wind generation capacity.

During the first three years of the 11th Plan period ending March 2010, India added 4.6 GW of wind power capacity. With over a year to go before the current plan period is over it is very likely that Indian wind power installations will meet and exceed the 11th plan-period target, which will be a record of sorts as historically the targets have never been met through conventional thermal and hydro projects within a plan period.

Under the IEA's Reference scenario, India's wind power market is shown to shrink considerably to only about 600 MW per year by 2030. This translates into a total installed capacity of merely 24 GW by 2020 and 30.5 GW by 2030. Wind power would then produce close to 60 TWh every year by 2020 and 75 TWh by 2030, and save 35 MT of $CO_2$ in 2020 and 45 MT in 2030. Investment in wind power in India would drop to about US$910 million by 2030 (at 2010 $ value).

However under the GWEO scenarios, it is expected that by the end of 2015, between 24.7 GW and 29 GW will be installed in India. Under the moderate scenario this would reach almost 46 GW by 2020 and 108 GW by 2030. In this scenario, about US$9 billion would be invested in Indian wind power development every year by 2020, representing a quadrupling of the 2009 investment figures. Employment in the sector would grow from the currently estimated 28,000 jobs to over 84,000 by 2020 and 1,13,000 by 2030. The GWEO advanced scenarios show that wind power development in India could go much further depending upon adequate regulatory support and political will. By 2020, India could have 65 GW of wind power in operation, employing 1,70,000 people and saving 173 MT of $CO_2$ emissions each year. Investment by then would be to the tune of US$10.4 billion per year. The World Institute for Sustainable Energy (WISE) estimates deploying just the current generation of wind turbines could yield a potential onshore wind power capacity of 65–100 GW.

The Ministry of New and Renewable Energy (MNRE) has so far underplayed the potential of renewable energy (RE) sources in India. WISE did a revised estimate of the true potential of grid-connected RE in India as given in Table 9.4.

WISE sees its own numbers as a conservative estimation. With the present level of momentum established in India's wind sector, the ten years between 2020 and 2030 could see spectacular growth if some of the systemic barriers are addressed in a timely manner. With the political will geared towards fully exploiting the country's wind resource and reaping the accompanying economic, environmental and energy security benefits, the 'Advanced scenario' could be reached, which would see substantial wind power growth in many regions of the country. Wind power would then be instrumental in achieving a genuine energy revolution, putting India on the path to a sustainable energy future. India is now at a crossroads for making these decisions, which will determine the future of her energy system. As well as, to a great extent, the future of the planet (Table 9.5).

**Table 9.4** Grid connected renewable energy potential in India.

| Energy source | Capacity (MW) | Assumed plant load factor | Annual energy generation [billion kWh] |
|---|---|---|---|
| Wind (onshore) | 1,00,000 | 25 | 219 |
| Small hydro | 15,000 | 45 | 46 |
| Bagasse | 5000 | 60 | 26.3 |
| Biomass | 16,881 | 60 | 88.72 |
| Large hydro (existing and future) | 1,00,000 | 60 | 525.6 |
| Large hydro in Bhutan | 16,000 | 60 | 84.1 |
| Waste to energy | 5000 | 60 | 26.28 |
| Concentrated solar based power generation | 2,00,000 | 35 | 613.2 |
| Solar photovoltaic based power generation | 2,00,000 | 20 | 350.4 |
| Geothermal | 10,000 | 80 | 70.1 |
| Total | 6,62,881 | | 2049.70 |

**Table 9.5** Comparative wind power development across few Indian states.

| Particulars | AP | Gujarat | Karnataka | Kerala | MP | Maharashtra | Rajasthan | TN |
|---|---|---|---|---|---|---|---|---|
| Identified sites | 32 | 40 | 26 | 17 | 7 | 39 | 8 | 45 |
| Potential districts | 7 | 9 | 9 | 3 | 5 | 13 | 5 | 11 |
| Annual mean wind speed (m/sec) at 50 m mast height | 4.86–6.61 | 4.33–6.97 | 5.19–8.37 | 4.41–8.12 | 5.0–6.25 | 4.31–6.58 | 4.02–5.73 | 4.47–7.32 |
| Monitoring stations (Oct. 2010) | 63 | 69 | 49 | 27 | 37 | 112 | 36 | 68 |
| Operating stations (Dec. 2010) | 2 | 6 | 5 | – | 4 | 22 | 1 | 1 |
| Wind potential (MW) | 5394 | 10,609 | 8591 | 790 | 920 | 5439 | 5005 | 5374 |
| Inst. capacity (MW) (Dec. 2010) | 176.8 | 2005.30 | 1576.20 | 28 | 230.8 | 2201.60 | 1353.40 | 5502.90 |
| Untapped potential (MW) (Dec. 2010) | 5217.20 | 8603.80 | 7014.90 | 762 | 689.2 | 3237.40 | 3671.70 | 128.9* |

*Based on government estimated potential for wind power. Currently, at least another 3000 MW of projects are in the pipeline in Tamil Nadu.

## 9.4 Estimated wind power resource

The Centre for Wind Energy Technology (C-WET) published the Indian Wind Atlas in 2010, showing large areas with annual average wind power densities of more than 200 Watts/m$^2$ at 50 metres above ground level (MAGL). This is considered to be a benchmark criterion for establishing wind farms in India as per CWET and the MNRE. The potential sites have been classified according to annual mean wind power density ranging from 200 W/m$^2$ to 500 W/m$^2$. Most of the potential assessed sites have an annual mean wind power density in the range of 200–250 W/m$^2$ at 50 MAGL. The Wind Atlas has projected Indian wind power installable potential (name plate rating) as 49,130 MW at 2 per cent land availability. This is seen as a conservative estimate of wind power potential in India (Table 9.6).

**Table 9.6** State-wise generation and installed capacity (up to 31st March 2010).

| State | Cumulative generation (MU) | Cumulative installed capacity (MW) |
|---|---|---|
| Andhra Pradesh | 1451 | 138.4 |
| Gujarat | 8016 | 1934.6 |
| Karnataka | 9991 | 1517.2 |
| Madhya Pradesh | 554 | 230.8 |
| Maharashtra | 11,790 | 2108.1 |
| Rajasthan | 3938 | 1095.6 |
| Tamil Nadu | 41,100 | 5073.1 |
| Kerala | 110 | 28 |
| Total | 76,950 | 12,125.8 |

With the improvement in technology and increase in the hub height of the wind turbine it has become possible to generate more electricity than assumed in earlier estimates. Based on the resource assessment carried out by C-WET, wind speeds in India are in the low to moderate range except in few pockets like coastal southern Tamil Nadu and the Rann of Katch (Gujarat). Further India's as yet unassessed offshore wind potential was not included in the C-WET study.

## 9.5 Offshore wind power development

A long coastline and relatively low construction costs could make India a favoured destination for offshore wind power. Offshore wind development is a relatively new phenomenon, and Europe is the only sizeable market at present, with a total offshore capacity of 3 GW. The global offshore wind turbine segment has been dominated by two established players, Vestas and Siemens. However, there are other manufacturers active in the market such as REPower, Sinovel, Areva and Bard, with strong interest from GE Wind, Gamesa, XEMC and WinWinD (Table 9.7).

Special construction requirements make offshore wind power 1.5–2.5 times more expensive than onshore, making large-scale offshore deployment difficult in developing regions. The current average rated capacity of offshore wind turbines is 2.5 MW, as compared to average onshore wind turbine capacity of 1.06 MW (BTM ApS, 2010). It should be noted that most of the 4–6 MW turbines currently in the testing or early deployment stage are designed for offshore operation. If the government supported small capacity offshore demonstration projects, it could build confidence and bring in public and private investment in this sector in the years to come.

To examine the feasibility of offshore wind farms, C-WET conducted the first phase of its study at Dhanushkodi in Tamil Nadu. So far, the area around Dhanushkodi has shown good potential, where wind power density of 350–500 W/m$^2$ has been recorded. For the next stage, C-WET is currently awaiting approval from various government agencies.

Based on a study carried out by WISE on the clearances required for offshore projects, it is understood that more than 20 central and state ministries and departments would need to be involved in the process. As this technology is in its nascent stage in India, there is a need for specific policy framework for offshore wind power generation.

On the corporate side, there have been a few early moves on offshore wind in India. Oil and Natural Gas Corporation (ONGC) announced its plans to tap offshore wind power. Further, in June 2010, global majors like Areva, Siemens and GE announced their plans to explore offshore wind power opportunities in the country. Tata Power is the first private sector player to submit a formal request to the Government of Gujarat and Gujarat Maritime Board for approval of an offshore project in India.

**Table 9.7** Challenges for repowering.

| Challenge | Issues |
|---|---|
| Turbine ownership | Repowering will reduce the number of turbines, and there may not be one-to-one replacement. Thus, the issue of ownership needs to be handled carefully. |
| Land ownership | Multiple owners of wind farm land may create complications for repowering projects. |
| Power purchase agreement | PPAs were signed with the state utility for 10, 13 or 20 years and the respective electricity board may not be interested in discontinuing or revising the PPA before its stipulated time. |
| Electricity evacuation facilities | The current grid facilities are designed to support present generation capacities and may require augmentation and upgrading. |
| Additional costs | The additional decommissioning costs for old turbines (such as transport charges) need to be assessed. |
| Disposal of old turbines | There are various options such as scrapping, buy-back by the government or manufacturer or export. Local capacity may need to be developed. |
| Incentives | One of the primary barriers to repowering is the general lack of economic incentive to replace the older WTGs. In order to compensate for the additional cost of repowering, appropriate incentives are necessary. |
| Policy package | A new policy package should be developed which would cover additional project cost and add-on tariff by the State Electricity Regulatory Commissions (SERCs) and include a repowering incentive (on the lines of the recently introduced generation-based incentive scheme by MNRE). |

## 9.6 Wind turbine installations

Wind turbine generator (WTG) capacity addition in India has taken place at a CAGR of 24.67 per cent for the period of 1992–2010. The installed capacity increased from a modest base of 41.3 MW in 1992 to reach 13,065.78 MW by December 2010. The official installation figures show that amongst the states, Tamil Nadu ranks the highest both in terms of installed capacity and in terms of energy generation from wind, with shares of 41.8 and 53.4 per cent respectively. Other states like Gujarat, Maharashtra and Rajasthan have seen significant growth in wind capacity over the last 4–5 years, also due to a stable policy and regulatory regime (Table 9.8).

**Table 9.8** Average size of WTG (kW) installed each year.

| Country | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|
| China | 771 | 897 | 931 | 1079 | 1220 | 1360 |
| Denmark | 2225 | 1381 | 1875 | 850 | 2277 | 2368 |
| Germany | 1715 | 1634 | 1848 | 1879 | 1916 | 1977 |
| India | 767 | 780 | 926 | 986 | 999 | 1117 |
| Spain | 1123 | 1105 | 1469 | 1648 | 1837 | 1897 |
| Sweden | 1336 | 1126 | 1138 | 1670 | 1738 | 1974 |
| UK | 1695 | 2172 | 1953 | 2049 | 2256 | 2251 |
| USA | 1309 | 1466 | 1667 | 1669 | 1677 | 1731 |

## 9.7 Repowering potential

Repowering is the process of replacing older, smaller wind turbines with modern and more powerful machines, which would reap considerably more power from the same site. In India, about 46 per cent of the WTGs were rated below 500 kW in 2010, adding up to 2331.3 MW (about 18 per cent of cumulative installed capacity). Figure 9.1 shows state-wise repowering potential as of March 2009. Amongst the states with good wind potential Tamil Nadu leads with a repowering potential of more than 800 MW followed by Gujarat, Maharashtra, Andhra Pradesh and Karnataka. A special drive for repowering of old wind farms undertaken by the central government would encourage the industry to take this up on a larger scale. This could be done by way of creating suitable mechanisms and offering support along with financial incentives, to make new repowering projects viable. Currently, neither the states nor the central government provides dedicated policy support or incentives to encourage Indian wind power developers or investors to repower their old projects. However, there are some challenges to be addressed before a comprehensive repowering attempt in India. All these issues related to repowering can no doubt be resolved by learning from the experiences in other markets such as Denmark and Germany, although they are still at the early stages of their own repowering. These markets have introduced various incentive mechanisms and policies to encourage repowering, and done away with provisions that initially hampered repowering. If a sensible policy package is developed, many old sites can provide two to three times their current electricity generation after repowering.

## 9.8 Technology development trends

Modern wind power technology has come a long way in the last two decades, and both globally and in India, improved technology has slowly and steadily improved capacity utilisation. A key trend in the Indian industry is the development of multi-megawatt turbines installed at greater hub heights. Larger diameter rotors mean that a single wind power generator can capture more energy or more 'power per tower'. This allows WTGs to take advantage of higher altitudes with stronger winds and less turbulence (wind speed generally increases with height above the ground). Subsequently, larger machines have resulted in a steady increase in the capacity factor on average from 10–12 per cent in 1998 to 20–22 per cent in 2010.

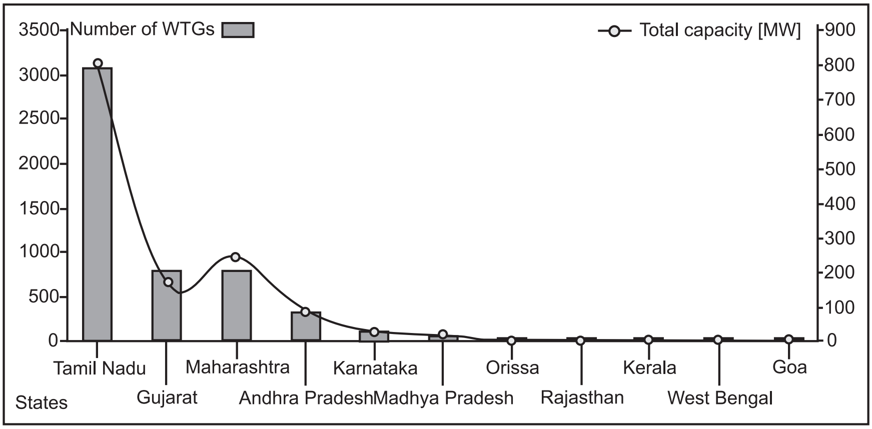



**Figure 9.1** State-level repowering potential in India

For two decades now, global average WTG power ratings have grown almost linearly, with current commercial machines rated on average in the range of 1.5–2.1 MW. The average size of WTGs installed in India has gradually increased from 767 kW in 2004 to 1117 kW in 2009. The shift in India to larger WTGs is a result of improved infrastructure available to handle bigger turbines and improved economics of the sector. As generator size increases, fixed overall project costs fall on a 'per unit of output' basis. Given that finding sites and establishing transmission corridors is a significant investment, developers need to maximise the use of available sites for wind power generation. Installing fewer high capacity turbines, versus installing a greater number of smaller turbines, reduces overall capital investment by lowering installation, maintenance and potentially real estate costs. For example, instead of siting ten 600 kW turbines on acres of land, developers can instead site only three 2.0 MW WTGs.

## 9.9 Investment in wind power sector

The Government of India has outlined ambitious capacity expansion and investment plans for the current plan period (2007–2012) and wind power projects form the majority of the proposed capacity addition. The total investments on development of RE during the plan period is expected to be in excess of US$15 billion (~Rs. 60,000 crores). The majority of this investment is being raised through domestic private investors, concessional financing from specialised government agencies and multilateral financial institutions.

Due to growing awareness of the benefits of wind power and evolving government priorities more banks and lending institutions are showing interest in funding these projects. On top of the financing spectrum is IREDA, the Indian Renewable Energy Development Agency, the apex nodal agency for renewable energy development in India and a funding arm of MNRE. The other government agencies that actively fund renewable energy projects are the Power Finance Corporation (PFC) and Rural Electrification Corporation (REC). Figure 9.2 shows annual sanctioned and actual installed capacity of SWTs and wind-solar hybrid systems.

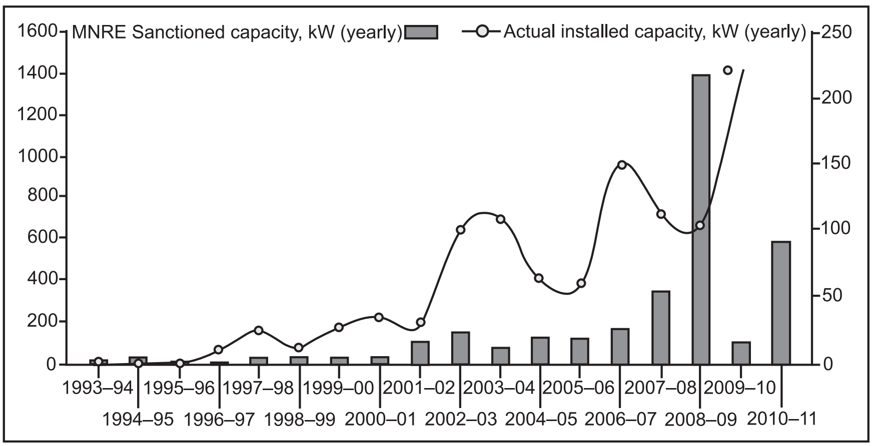



**Figure 9.2** Annual sanctioned and actual installed capacity of SWTs and wind-solar hybrid systems

The multilateral agencies such as the World Bank, the International Finance Corporation (IFC), and the Asian Development Bank (ADB), as well as bilateral agencies such as KFW (German Development Bank) have also stepped up their assistance to the sector in the last few years. Prominent domestic banks that fund renewable projects are IDBI, ICICI, IFCI, SBI and PNB among others. Foreign banks such as Standard Chartered, RBS India (formerly known as ABN Amro) and Rabobank are also providing renewable energy project financing. Currently, the market in India for the RE business is growing at an annual rate of 15 per cent. The scope for private investment in RE is estimated at about US$3 billion per annum. Given the evolving regulatory and policy regime, the business outlook is generally positive at this time. Proposed policy guidance and regulations are also coming into place to further strengthen this rate of growth.

## 9.10 Small wind and hybrid systems

The global market for small wind turbines (SWTs) has been on the upswing over the last two to three years. This is driven by rapidly growing energy demand, higher fossil fuel prices and improved SWT technology, which can be deployed for a diverse pool of applications, both in 'grid-tied' and 'standalone' modes. With the increasing shortfall in power supply and energy across the country, India could benefit significantly from exploiting the potential of micro-generation technologies that can meet energy needs under the distributed generation mode, so as to provide long-term solutions. WISE estimates India's micro-generation potential at about 83 GW. However, costs are a major hurdle and policy support needs to be oriented towards promoting mass manufacturing and early adoption of these microgeneration options. Although a small annual market for such systems (~150–200 kW) currently exists in India, it is largely driven by the capital subsidy program of the MNRE. Most of the current installations are of the standalone type. Figure 9.3 shows state-wise distribution of wind-solar hybrid systems.

The 'small wind energy and hybrid systems' program initiated in 1994 by the MNRE focused solely on small wind energy and hybrid systems. The objective of the program is to develop technology and promote applications of water pumping windmills and aero-generators/wind-solar hybrid systems. Although the program helped to promote awareness of small wind systems in India, it created interest only among select users and has yet to make a real impact. The implementation of the program was extended in April 2010 to the fiscal year 2011–12. The physical annual target was set to installed 500 kW aero-generator/wind-solar hybrid systems and 25 water pumping windmills with estimated financial budget of Rs. 50 million over 2010–2012.

The program is implemented through State Nodal Agencies (SNA) mainly in Andhra Pradesh, Assam, Bihar, Gujarat, Karnataka, Kerala, Maharashtra, Rajasthan, Sikkim, Tamil Nadu, Goa, and West Bengal and the Andaman and Nicobar Islands. Manufacturers of water-pumping windmills, aerogenerators, and wind-solar hybrid systems are also eligible to market the systems directly to users. The program is being extended to other potential states.

An aggregate capacity of 1.07 MW of aerogenerators or hybrid systems was installed under the program up to December 2010. Interestingly, almost 57 per cent of the total cumulative installations in the country are in Maharashtra followed by Goa, Karnataka, West Bengal, Manipur and Tamil Nadu. Almost all the projects sanctioned by the MNRE and those actually commissioned availed themselves of capital subsidy benefits from the Ministry.

## 9.11 Barriers to higher growth

The low utilisation of the country's wind power potential so far is attributable to several factors, including lack of an appropriate regulatory framework to facilitate purchase of renewable energy from outside the host state, inadequate grid connectivity; high wheeling and open access charges in some states, delays in acquiring land and obtaining statutory clearances.

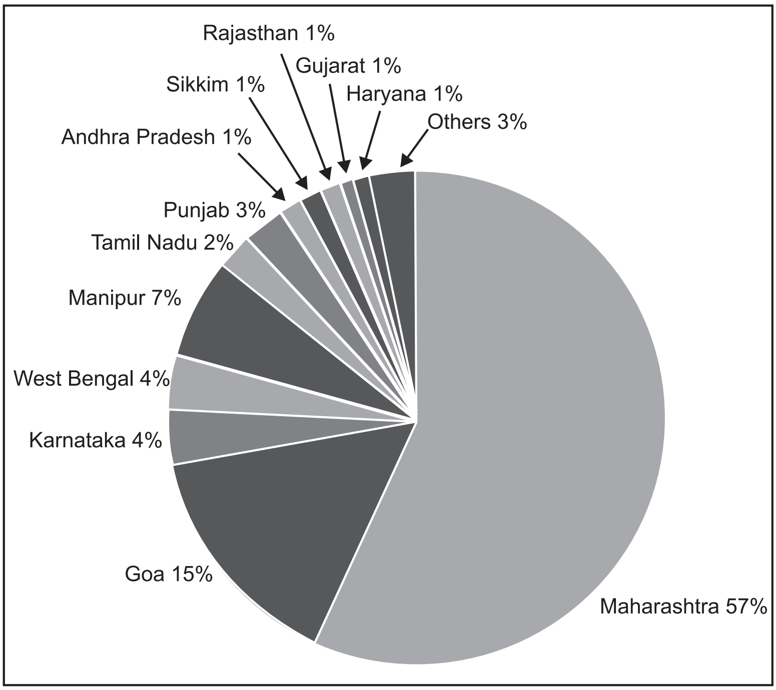



**Figure 9.3** State-wise distribution of wind–solar hybrid systems

In 2010, India installed a record 2.1 GW of new wind power capacity. For this growth to be maintained it is essential that the industry is supported by a predictable policy and regulatory environment. Proposed amendments to India's tax laws (such as the Direct Tax Code; Goods and Services Tax) will have an impact on the investment portfolio of wind power.

Besides these there are other potential barriers to achieving higher growth rates in the short-to-medium term. The main reason for the growth of wind power has been the availability of accelerated depreciation (AD), providing the facility to offset taxes on income from other sources. With the possible introduction of the DTC from the next fiscal year (2012–13), the quantum of this benefit could be affected, which could have an impact on the investments in the Indian wind sector.

The Generation Based Incentive (GBI) scheme has not attracted as many Independent power producers as envisaged, since the investors are of the opinion that the current rate of Re. 0.5/kWh is not adequate or in line with the fiscal benefits offered under the AD scheme, and the two are mutually exclusive. Further, the multitude of regulatory agencies adds to the confusion—there is the Central Electricity Regulatory Commission (CERC) and each state also has a State Electricity Regulatory Commission (SERC). The CERC issues guidelines for determining the feed-in-tariff from RE sources and these are applicable to central government power generating stations and those who transmit power in the interstate corridor. However, this is applicable to a very small number of power producers and the vast majority is still covered by the tariff determined by the SERCs. This duality is not useful. For example, an SERC could determine the tariff which may or may not be equivalent to the tariff determined by the CERC. This has a major impact on the project developers.

Inadequate grid infrastructure is another key issue that needs to be addressed urgently. Across most of those states with significant wind potential, the grid does not have sufficient spare capacity to be able to evacuate ever increasing amount of wind power. As a result, the state distribution utilities are reluctant to accept more power and on a merit order basis prefer thermal power. Thus, there is an urgent need to augment the grid capacity and the regional Southern Grid needs to be connected with the rest of the country on a realtime basis. This requires better forecasting of power demand across the nation, and a modernisation of the grid.

In most of the states availability of land for wind farms is a contentious issue. Even if private lands are available, conversion of land use status from agricultural to non-agricultural is a time consuming process. Further, if the land is close to a protected area or forest lands then obtaining clearance from forest authorities for using the forest land for wind power generation is also time consuming.

Current and projected growth rates for wind power development in India are putting increasing strain on the WTG manufacturing sector, and the component supply chain needs to be improved. It would be beneficial for the small and medium enterprises (SMEs) to have access to concessional financing to bear the risks related to production capacity augmentation. As the industry grows, there will be demand for trained manpower and accordingly, the academic curriculum may need to be modified.

# 10
# Hydroelectric power

## 10.1 Introduction

It is a form of energy—a renewable resource. Hydropower provides about 96 per cent of the renewable energy in the United States. Other renewable resources include geothermal, wave power, tidal power, wind power, and solar power. Hydroelectric power plants do not use up resources to create electricity nor do they pollute the air, land or water, as other power plants may. Hydroelectric power has played an important part in the development of world's electric power industry. Both small and large hydroelectric power developments were instrumental in the early expansion of the electric power industry.

Hydroelectric power comes from flowing water—winter and spring runoff from mountain streams and clear lakes. Water, when it is falling by the force of gravity, can be used to turn turbines and generators that produce electricity.

Hydroelectric power is important to our Nation. Growing populations and modern technologies require vast amounts of electricity for creating, building, and expanding. In the 1920s, hydroelectric plants supplied as much as 40 per cent of the electric energy produced. Although the amount of energy produced by this means has steadily increased, the amount produced by other types of power plants has increased at a faster rate and hydroelectric power presently supplies about 10 per cent of the electrical generating capacity of the United States. Hydropower is an essential contributor in the national power grid because of its ability to respond quickly to rapidly varying loads or system disturbances, which base load plants with steam systems powered by combustion or nuclear processes cannot accommodate.

Reclamation's 58 power plants throughout the Western United States produce an average of 42 billion kWh (kilowatt-hours) per year, enough to meet the residential needs of more than 14 million people. This is the electrical energy equivalent of about 72 million barrels of oil. Hydroelectric power plants are the most efficient means of producing electric energy. The efficiency of today's hydroelectric plant is about 90 per cent. Hydroelectric plants do not create air pollution, the fuel—falling water—is not consumed, projects have long lives relative to other forms of energy generation, and hydroelectric generators respond quickly to changing system conditions. These favourable characteristics continue to make hydroelectric projects attractive sources of electric power.

## 10.2 Hydropower

The power of water was exploited in the ancient world for irrigation, grinding corn, metal forging, and mining. Waterwheels were common in Western Europe by the end of the first millennium; over 5000 waterwheels were recorded in the Domesday book of 1086 shortly after the Norman conquest of England. The early waterwheels were of the undershot design (Fig. 10.1a) and very inefficient. The development of overshot waterwheels (Fig. 10.1b), and improvements in the shape of the blades to capture more of the incident kinetic energy of the stream, led to higher efficiencies.

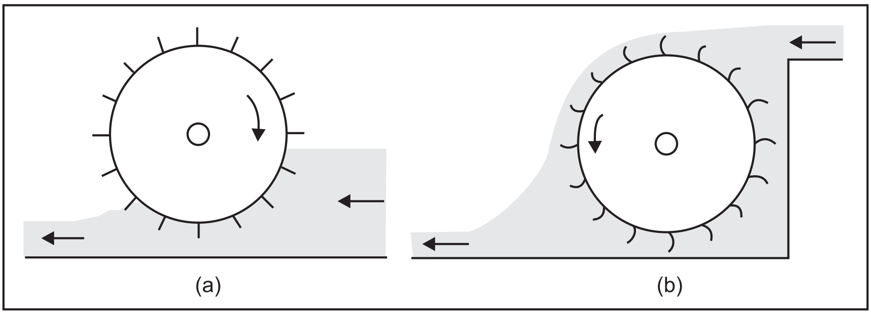



**Figure 10.1** (a) Undershot, and (b) overshot waterwheels

A breakthrough occurred in 1832 with the invention of the Fourneyron turbine, a fully submerged vertical axis device that achieved efficiencies of over 80 per cent. Fourneyron's novel idea was to employ fixed guide vanes that directed water outwards through the gaps between moving runner blades as shown in Fig. 10.2. Many designs of water turbines incorporating fixed guide vanes and runners have been developed since. Modern water turbines are typically over 90 per cent efficient.

The main economic advantages of hydropower are low operating costs, minimal impact on the atmosphere, quick response to sudden changes in electricity demand, and long plant life—typically 40 years or more before major refurbishment. However, the capital cost of construction of dams is high and the payback period is very long. There are also serious social and environmental issues to be considered when deciding about a new hydroelectric scheme, including the displacement of population, sedimentation, changes in water quality, impact on fish, and flooding. Mountainous countries like Norway and Iceland are virtually self-sufficient in hydropower but, in countries where the resource is less abundant, hydropower is mainly used to satisfy peak-load demand. The hydroelectric capacity by country and the largest sites are shown in Table 10.1.

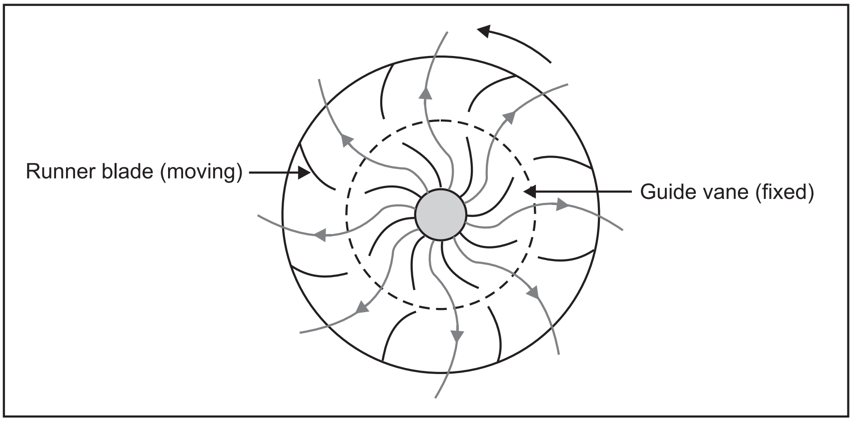



**Figure 10.2** Fourneyron water turbine

**Table 10.1** Installed hydropower.

| Country | | Hydroelectric capacity in 2005 (GW) |
|---|---|---|
| USA | | 120 |
| Canada | | 98 |
| China | | 95 |
| Brazil | | 85 |
| Norway | | 54 |
| Japan | | 52 |
| **Largest sites for hydropower** | | |
| Country | Site | Hydroelectric capacity (GW) |
| China | Three Gorges | 18.2 |
| Brazil/Paraguay | Itaipu | 12.6 |
| Venezuela | Guri | 10.3 |
| USA | Grand Coulee | 6.9 |
| Russia | Sayano–Shushenk | 6.4 |
| Russia | Krasnoyarsk | 6 |

## 10.3 Power output from a dam

Consider a turbine situated at a vertical distance h (called the head) below the surface of the water in a reservoir (Fig. 10.3). The power output P is the product of the efficiency η, the potential energy per unit volume ρgh, and the volume of water flowing per second Q, i.e.

$$P = \eta \rho g h Q \qquad \text{... (10.1)}$$

Note that the power output depends on the product hQ. Thus a high dam with a large h and a small Q can have the same power output as a run-of-river installation with a small h and large Q. The choice of which design of water turbine is suitable for a particular location depends on the relative magnitudes of h and Q.

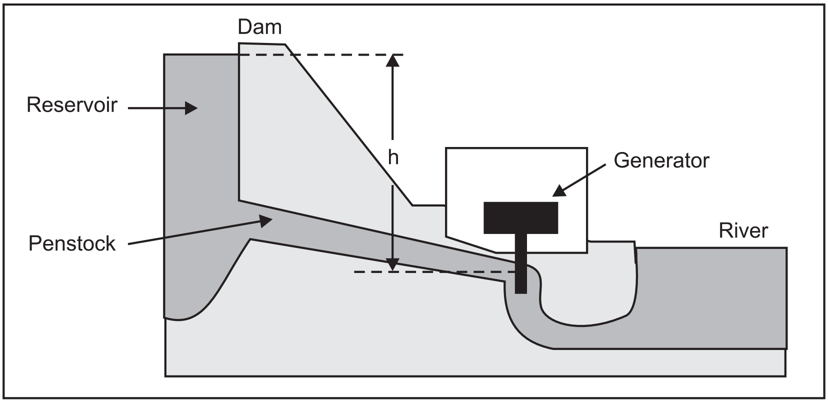



**Figure 10.3** Hydroelectric plant

## 10.4 Measurement of volume flow rate using a weir

For power extraction from a stream it is important to be able to measure the volume flow rate of water. One particular method diverts the stream through a straight-sided channel containing an artificial barrier called a weir (Fig. 10.4). The presence of the weir forces the level of the fluid upstream of the weir to rise. The volume flow rate per unit width is related to the height of the undisturbed level of water gmin above the top of the weir by the formula:

$$Q = g^{1/2}(2/3\ \gamma_{min})^{3/2} \qquad \text{... (10.2)}$$

## 10.5 Water turbines

When water flows through a waterwheel, the water between the blades is almost stationary. Hence the force exerted on a blade is essentially due to the difference in pressure across the blade. In a water turbine, however, the water is fast moving and the turbine extracts kinetic energy from the water. There are two basic designs of water turbines: impulse turbines and reaction turbines.

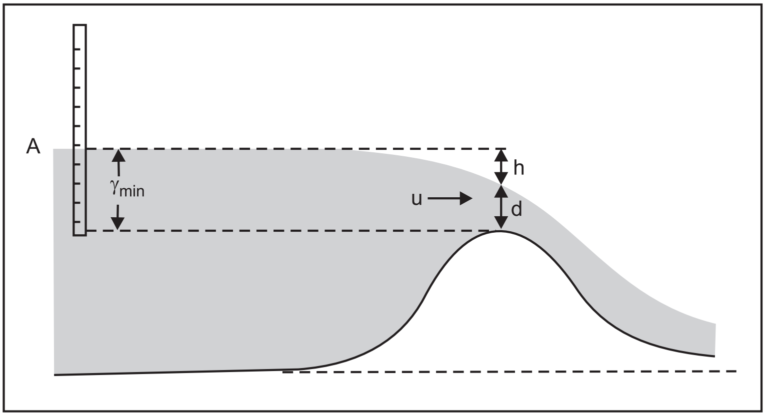



**Figure 10.4** Flow over broad-crested weir

In an impulse turbine, the blades are fixed to a rotating wheel and each blade rotates in air, apart from when the blade is in line with a high speed jet of water. In a reaction turbine, however, the blades are fully immersed in water and the thrust on the moving blades is due to a combination of reaction and impulse forces. An impulse turbine called a Pelton wheel is shown in Fig. 10.5. In this example there are two symmetrical jets, and each jet imparts an impulse to the blade equal to the rate of change of momentum of the jet. The speed of the jet is controlled by varying the area of the nozzle using a spear valve. Thomas Pelton went to seek his fortune in the Californian Gold Rush during the nineteenth century. By the time he arrived on the scene the easy pickings had already been taken and the remaining gold had to be extracted from rocks that needed to be crushed.

Impulse turbines were being used to drive the mills to grind the rocks into small lumps. Pelton observed the motion of the turbine blades and deduced that not all the momentum of the jets was being utilised. He realised that some momentum was being lost because the water splashed in all directions on striking the blades.

He redesigned the cups so that the direction of the splash was opposite to that of the incident jet. This produced a marked improvement in efficiency and Pelton thereby made his fortune.

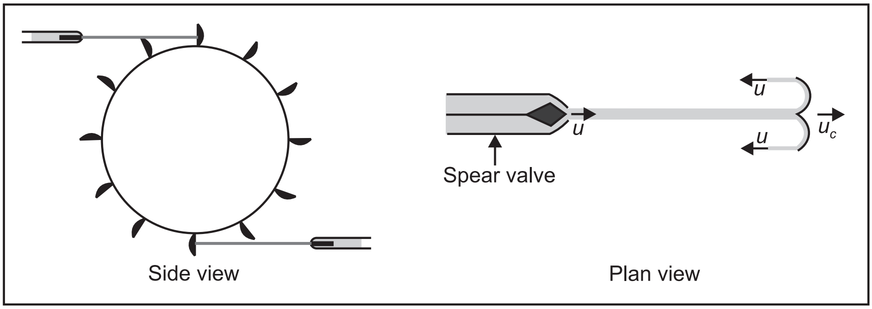



**Figure 10.5** Impulse turbine (Pelton wheel)

To calculate the maximum power output from a Pelton wheel, we consider a jet moving with velocity u and the cup moving with velocity uc. Relative to the cup, the velocity of the incident jet is $(u - u_c)$ and the velocity of the reflected jet is $-(u - u_c)$. Hence the total change in the velocity of the jet is $-2(u - u_c)$. The mass of water striking the cup per second is $\rho Q$, so the force on the cup is given by:

$$F = 2\rho Q(u - u_c) \quad \text{... (10.3)}$$

The power output P of the turbine is the rate at which the force F does work on the cup in the direction of motion of the cup, i.e.

$$P = Fu_c = 2\rho Q\,(u - u_c)u_c \quad \text{... (10.4)}$$

To derive the maximum power output we put $dP/du_c = 0$, yielding $u_c = ½u$.

Substituting in Eq. 10.4 then yields the maximum power as:

$$P_{max} = ½\rho Qu^2 \quad \text{... (10.5)}$$

Thus the maximum power output is equal to the kinetic energy incident per second.

As in the Fourneyron turbine, modern reaction turbines use fixed guide vanes to direct water into the channels between the blades of a runner mounted on a rotating wheel (Fig. 10.6). However, the direction of radial flow is inward (In the Fourneyron turbine, the outward flow caused problems when the flow rate was either increased or decreased).

The most common designs of reaction turbines are the Francis turbine and the Kaplan turbine. In a Francis turbine the runner is a spiral annulus, whereas in the Kaplan turbine it is propeller-shaped. In both designs the kinetic energy of the water leaving the runner is small compared with the incident kinetic energy.

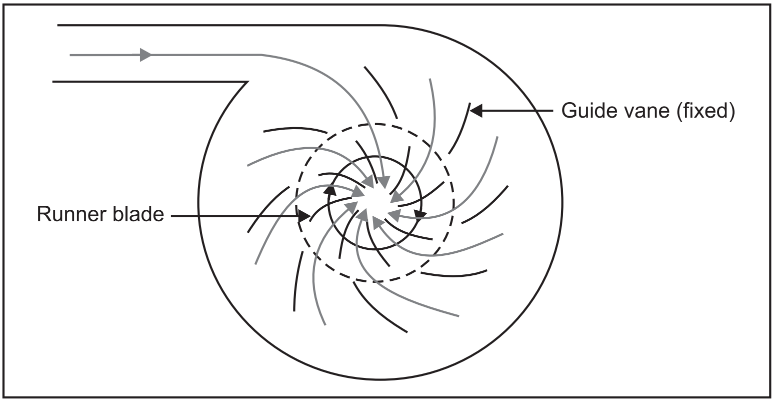



**Figure 10.6** Reaction turbine (plan view)

The term 'reaction turbine' is somewhat misleading in that it does not completely describe the nature of the thrust on the runner. The magnitude of the reaction can be quantified by applying Bernoulli's equation to the water entering and leaving the runner, i.e.

$$\frac{p_1}{\rho} + \frac{1}{2}q_1^2 = \frac{p_2}{\rho} + \frac{1}{2}q_2^2 + E \qquad \text{... (10.6)}$$

where, E is the energy per unit mass of water transferred to the runner. Consider two cases: (i) $q_1 = q_2$, and (ii) $p_1 = p_2$. In case (i), Eq. 10.6 reduces to:

$$E = \frac{p_1 - p_2}{\rho} \qquad \text{... (10.7)}$$

i.e. the energy transferred arises from the difference in pressure between inlet and outlet. In case (ii), E is given by:

$$E = \frac{1}{2}(q_1^2 - q_2^2) \qquad \text{... (10.8)}$$

i.e. the energy transferred is equal to the difference in the kinetic energy between inlet and outlet. In general we define the degree of reaction R as:

$$R = \frac{p_1 - p_2}{\rho E} = 1 - \frac{(q_1^2 - q_2^2)}{2E} \qquad \text{... (10.9)}$$

The velocity diagrams in the laboratory frame of reference for an impulse turbine and a reaction turbine are shown in Fig. 10.7(a) and (b), respectively. The symbols u, q and w denote the velocity of the runner blade, the absolute velocity of the fluid, and the velocity of the fluid relative to the blade. Figure 10.7 shows the velocity triangles on the outer radius of the runner $r = r_1$ and the inner radius $r = r_2$. The runner rotates with angular velocity ω, so that the velocity of the blade is $u_1 = r_1\omega$ on the outer radius and $u_2 = r_2\omega$ on the inner radius. The torque on the runner is:

$$T = \rho Q(r_1 q_1 \cos\beta_1 - r_2 u_2 \cos\beta_2).$$

Putting $r_1 = u_1/\omega$ and $r_2 = u_2/\omega$, the work done per second is given by:

$$P = T\omega = \rho Q(u_1 q_1 \cos\beta_1 - u_2 q_2 \cos\beta_2).$$

The term in brackets represents the energy per unit mass:

$$E = u_1 q_1 \cos\beta_1 - u_2 q_2 \cos\beta_2. \quad \text{... (10.10)}$$

Equating the incident power due to the head of water h from Eq. 10.1 to the power output of the turbine, given by Euler's turbine equation, we have

$$\eta\rho ghQ = \rho Q(u_1 q_1 \cos\beta_1 - u_2 q_2 \cos\beta_2).$$

The term $\rho Q u_2 q_2 \cos\beta_2$ represents the rate at which kinetic energy is removed by the water leaving the runner. We define the hydraulic efficiency as:

$$\eta = \frac{u_1 q_1 \cos\beta_1 - u_2 q_2 \cos\beta_2}{gh} \quad \text{... (10.11)}$$

The maximum efficiency is achieved when the fluid leaves the runner at right angles to the direction of motion of the blades, i.e. when $\beta_2 = \pi/2$ so that $\cos\beta_2 = 0$. Equation 10.11 then reduces to

$$\eta_{max} = \frac{u_1 q_1 \cos\beta_1}{gh} \quad \text{... (10.12)}$$

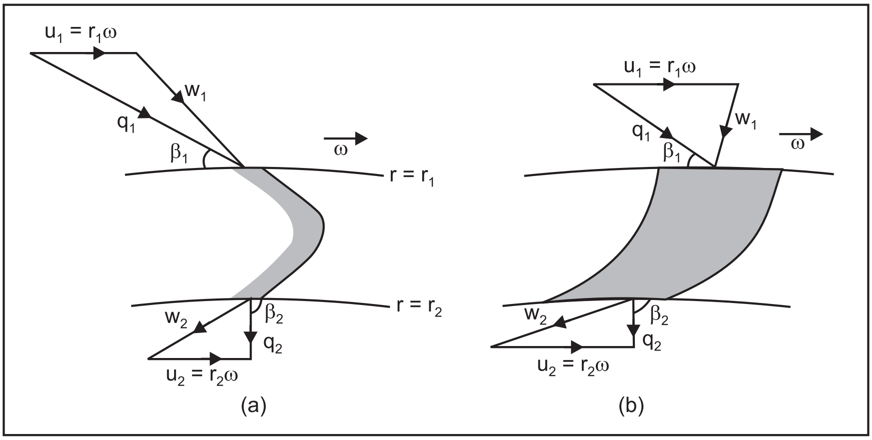



**Figure 10.7** Velocity diagrams for: (a) an impulse turbine, and (b) a reaction turbine

### 10.5.1 Choice of water turbine

The choice of water turbine depends on the site conditions, notably on the head of water h and the water flow rate Q. Figure 10.8 indicates which turbine is most suitable for any particular combination of head and flow rate. Impulse turbines are suited for large h and a low Q, e.g. fast moving mountain streams. Kaplan turbines are suited for low h and large Q (e.g. run-of-river sites) and Francis turbines are usually preferred for large Q and large h, e.g. dams. A useful parameter for choosing the most suitable turbine is the shape (or type) number S.

## 10.6 Impact, economics and prospects of hydropower

Hydropower sites tend to have a large impact on the local population. Over 1.1 million people were displaced by the Three Gorges dam in China, and it has been estimated that 30–60 million people worldwide have had to be relocated due to hydropower. Proposed hydropower plants often provoke controversy and in some countries public opposition to hydropower has stopped all construction except on small-scale projects. Also, dams sometimes collapse for various reasons, e.g. overspilling of water, inadequate spillways, foundation defects, settlement, slope instability, cracks, erosion, and freak waves from landslides in steep-sided valleys around the reservoir. As with nuclear plants, the risk of major accidents is small but the consequences can be catastrophic. Given the long lifetime of dams, even a typical failure rate as low as one per 6000 dam years means that any given dam has a probability of about 1 per cent that it will collapse at sometime in its life. In order to reduce the environmental impact and the consequences of dam failure, the question arises as to whether it is better to build a small number of large reservoirs or a large number of small ones. Though small reservoirs tend to be more acceptable to the public than large ones, they need a much larger total reservoir area than a single large reservoir providing the same volume of stored water.

An argument in favour of hydropower is that it does not produce greenhouse gases or acid rain gases. However, water quality may be affected both upstream and downstream of a dam due to increases in the concentrations of dissolved gases and heavy metals. These effects can be mitigated by inducing mixing at different levels and oxygenating the water by auto-venting turbines. The installation of a hydropower installation can also have a major impact on fish due to changes in the habitat, water temperature, flow regime, and the loss of marine life around the turbines.

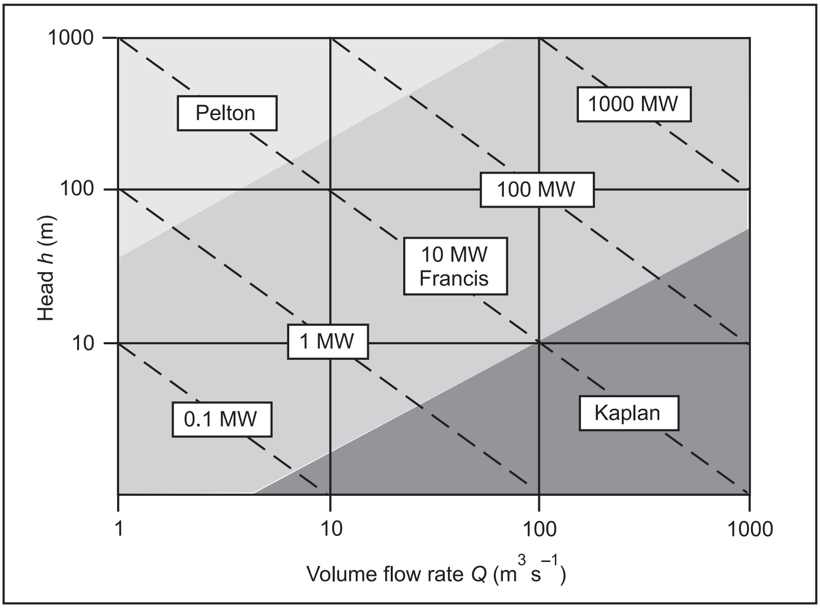



**Figure 10.8** Choice of turbine in terms of head h and volume flow rate Q

The capital cost of construction of hydropower plants is typically much larger than that for fossil fuel plants. Another cost arises at the end of the effective life of a dam, when it needs to be decommissioned. The issue as to who should pay for the cost involved in decommissioning is similar to that for nuclear plants: the plant owners, the electricity consumers or the general public? On the positive side, production costs for hydropower are low because the resource (rainfall) is free. Also, operation and maintenance costs are minimal and lifetimes are long: typically 40–100 years. The efficiency of a hydroelectric plant tends to decrease with age due to the build-up of sedimentation trapped in the reservoir. This can be a life-limiting factor because the cost of flushing and dredging is usually prohibitive.

The economic case for any hydropower scheme depends critically on how future costs are discounted. Discounting reduces the benefit of long-term income, disadvantaging hydropower compared with quick payback schemes such as CCGT generation. Hydropower schemes therefore tend to be funded by governmental bodies seeking to improve the long-term economic infrastructure of a region rather than by private capital. Despite the strong upward trend in global energy demand, the prospects for hydropower are patchy. In the developed world the competitive power market has tilted the balance away from capitally intensive projects towards plants with rapid payback of capital. As long as relatively cheap fossil fuels are available, the growth of hydropower is likely to be limited to parts of the world where water is abundant and labour costs for construction are low. However, it is a source of carbon-free energy and its importance would be enhanced by restrictions on carbon emissions aimed at tackling global warming.

## 10.7 How hydropower works

Hydroelectric power comes from water at work, water in motion. It can be seen as a form of solar energy, as the sun powers the hydrologic cycle which gives the earth its water. In the hydrologic cycle (Fig. 10.9), atmospheric water reaches the earth's surface as precipitation. Some of this water evaporates, but much of it either percolates into the soil or becomes surface runoff. Water from rain and melting snow eventually reaches ponds, lakes, reservoirs or oceans where evaporation is constantly occurring.

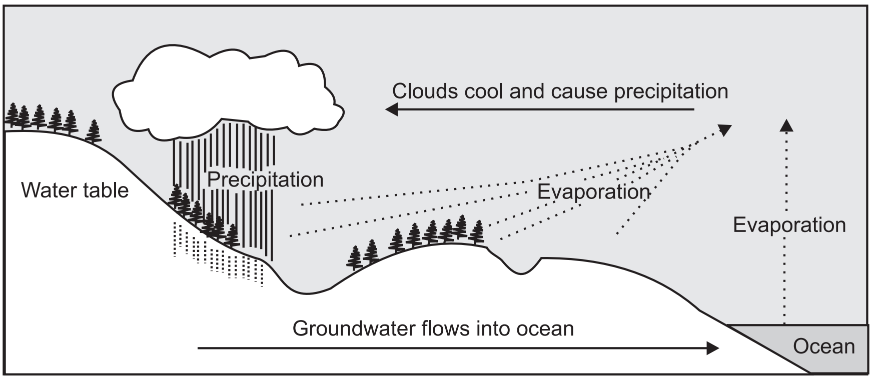



**Figure 10.9** Hydrological cycle

Moisture percolating into the soil may become groundwater (subsurface water), some of which also enters water bodies through springs or underground streams. Groundwater may move upward through soil during dry periods and may return to the atmosphere by evaporation.

Water vapour passes into the atmosphere by evaporation then circulates, condenses into clouds, and some returns to earth as precipitation. Thus, the water cycle is complete. Nature ensures that water is a renewable resource.

### 10.7.1 Generating power

In nature, energy cannot be created or destroyed, but its form can change. In generating electricity, no new energy is created. Actually one form of energy is converted to another form. To generate electricity, water must be in motion. This is kinetic (moving) energy. When flowing water turns blades in a turbine, the form is changed to mechanical (machine) energy. The turbine turns the generator rotor which then converts this mechanical energy into another energy form—electricity. Since water is the initial source of energy, we call this hydroelectric power or hydropower for short. At facilities called hydroelectric power plants, hydropower is generated (Fig. 10.10). Some power plants are located on rivers, streams, and canals, but for a reliable water supply, dams are needed. Dams store water for later release for such purposes as irrigation, domestic and industrial use, and power generation. The reservoir acts much like a battery, storing water to be released as needed to generate power. The dam creates a 'head' or height from which water flows. A pipe (penstock) carries the water from the reservoir to the turbine. The fast-moving water pushes the turbine blades, something like a pinwheel in the wind. The waters force on the turbine blades turns the rotor, the moving part of the electric generator. When coils of wire on the rotor sweep past the generator's stationary coil (stator), electricity is produced.

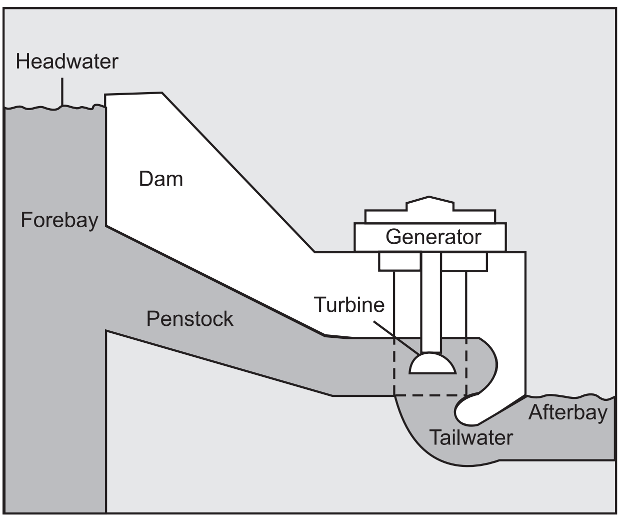



**Figure 10.10** Hydroelectric power plants

This concept was discovered by Michael Faraday in 1831 when he found that electricity could be generated by rotating magnets within copper coils. When the water has completed its task, it flows on unchanged to serve other needs.

## 10.7.2 Transmitting power

Once the electricity is produced, it must be delivered to where it is needed—our homes, schools, offices, factories, etc. Dams are often in remote locations and power must be transmitted over some distance to its users. Vast networks of transmission lines and facilities are used to bring electricity to us in a form we can use. All the electricity made at a power plant comes first through transformers which raise the voltage so it can travel long distances through power lines. (Voltage is the pressure that forces an electric current through a wire.) At local substations, transformers reduce the voltage so electricity can be divided up and directed throughout an area (Fig. 10.11). Transformers on poles (or buried underground, in some neighbourhoods) further reduce the electric power to the right voltage for appliances and use in the home. When electricity gets to our homes, we buy it by the kilowatt-hour, and a meter measures how much we use. While hydroelectric power plants are one source of electricity, other sources include power plants that burn fossil fuels or split atoms to create steam which in turn is used to generate power. Gas-turbine, solar, geothermal, and wind-powered systems are other sources. All these power plants may use the same system of transmission lines and stations in an area to bring power to you. By use of this ‘power grid’, electricity can be interchanged among several utility systems to meet varying demands. So the electricity lighting your reading lamp now may be from a hydroelectric power plant, a wind generator, a nuclear facility, or a coal, gas or oil-fired power plant or a combination of these (Fig. 10.12).

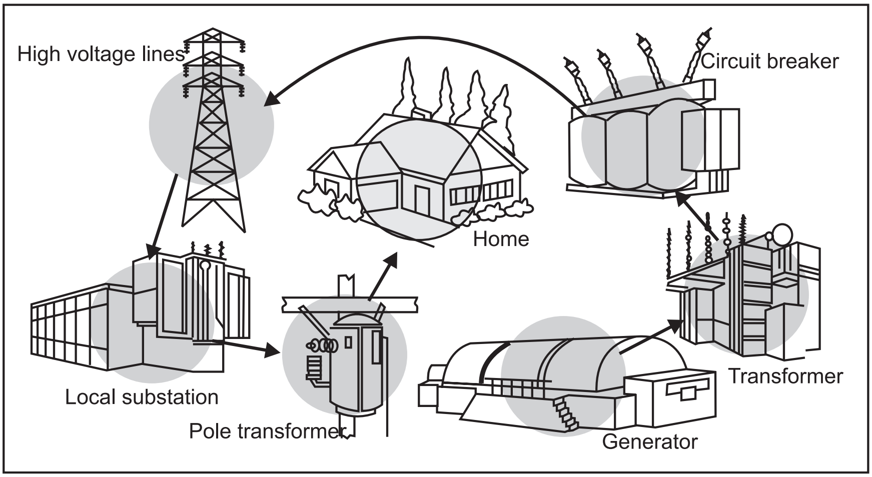



**Figure 10.11** Transmitting power

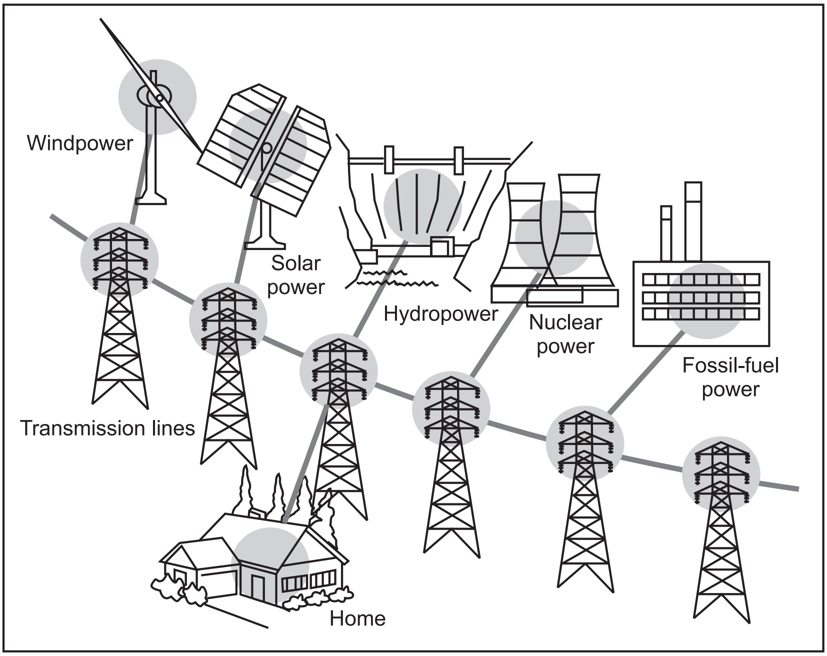



**Figure 10.12** Power plants

The area where you live and its energy resources are prime factors in determining what kind of power you use. For example, in Washington State hydroelectric power plants provided approximately 80 per cent of the electrical power during 2007. In contrast, in Ohio during the same year, almost 87 per cent of the electrical power came from coal-fired power plants due to the area's ample supply of coal.

Electrical utilities range from large systems serving broad regional areas to small power companies serving individual communities. Most electric utilities are investor-owned (private) power companies. Others are owned by towns, cities, and rural electric associations. Surplus power produced at facilities owned by the Federal Government is marketed to preference power customers (A customer given preference by law in the purchase of federally generated electrical energy which is generally an entity which is nonprofit and publicly financed.) by the Department of Energy through its power marketing administrations.

## 10.7.3 How power is computed

Before a hydroelectric power site is developed, engineers compute how much power can be produced when the facility is complete. The actual output of energy at a dam is determined by the volume of water released (discharge) and the vertical distance the water falls (head). So, a given amount of water falling a given distance will produce a certain amount of energy. The head and the discharge at the power site and the desired rotational speed of the generator determine the type of turbine to be used. The head produces a pressure (water pressure), and the greater the head, the greater the pressure to drive turbines. This pressure is measured in pounds of force (pounds per square inch). More head or faster flowing water means more power.

To find the theoretical horsepower (the measure of mechanical energy) from a specific site, this formula is used:

$$THP = (Q \times H)/8.8$$

where, THP = theoretical horsepower
Q = flow rate in cubic feet per second (cfs)
H = head in feet
8.8 = a constant

A more complicated formula is used to refine the calculations of this available power. The formula takes into account losses in the amount of head due to friction in the penstock and other variations due to the efficiency levels of mechanical devices used to harness the power.

To find how much electrical power we can expect, we must convert the mechanical measure (horsepower) into electrical terms (watts). One horsepower is equal to 746 watts.

### 10.7.4 Turbines

While there are only two basic types of turbines (impulse and reaction), there are many variations. The specific type of turbine to be used in a power plant is not selected until all operational studies and cost estimates are complete. The turbine selected depends largely on the site conditions.

A reaction turbine is a horizontal or vertical wheel that operates with the wheel completely submerged, a feature which reduces turbulence. In theory, the reaction turbine works like a rotating lawn sprinkler where water at a central point is under pressure and escapes from the ends of the blades, causing rotation. Reaction turbines are the type most widely used. Various types of turbine are shown in Fig. 10.13.

An impulse turbine is a horizontal or vertical wheel that uses the kinetic energy of water striking its buckets or blades to cause rotation. The wheel is covered by a housing and the buckets or blades are shaped so they turn the flow of water about 170 degrees inside the housing. After turning the blades or buckets, the water falls to the bottom of the wheel housing and flows out.

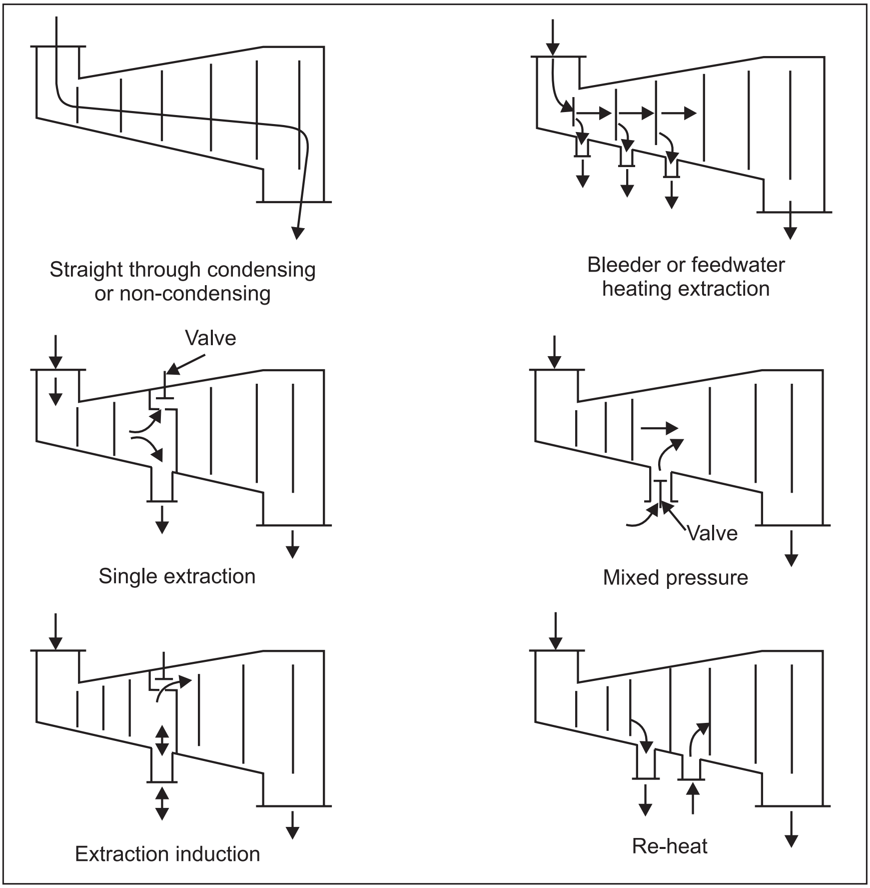



**Figure 10.13** Various types of turbine

## 10.8 Modern concepts and future role

Hydropower does not discharge pollutants into the environment; however, it is not free from adverse environmental effects. Considerable efforts have been made to reduce environmental problems associated with hydropower operations, such as providing safe fish passage and improved water quality in the past decade at both Federal facilities and non-Federal facilities licensed by the Federal Energy Regulatory Commission. Efforts to ensure the safety of dams and the use of newly available computer technologies to optimise operations have provided additional opportunities to improve the environment. Yet, many unanswered questions remain about how best to maintain the economic viability of hydropower in the face of increased demands to protect fish and other environmental resources.

Reclamation actively pursues research and development (R&D) programs to improve the operating efficiency and the environmental performance of hydropower facilities.

Hydropower research and development today is primarily being conducted in the following areas:

1. Fish passage, behaviour, and response
2. Turbine-related projects
3. Monitoring tool development
4. Hydrology
5. Water quality
6. Dam safety
7. Operations and maintenance
8. Water resources management

Reclamation continues to work to improve the reliability and efficiency of generating hydropower. Today, engineers want to make the most of new and existing facilities to increase production and efficiency. Existing hydropower concepts and approaches include:

1. Uprating existing power plants
2. Developing small plants (low-head hydropower)
3. Peaking with hydropower
4. Pumped storage
5. Tying hydropower to other forms of energy

### 10.8.1 Uprating

The uprating of existing hydroelectric generator and turbine units at power plants is one of the most immediate, cost-effective, and environmentally acceptable means of developing additional electric power. Since 1978, Reclamation has pursued an aggressive uprating program which has added more than 16,00,000 kW to Reclamation's capacity. Reclamation's uprating program has essentially provided the equivalent of another major hydroelectric facility of the approximate magnitude of Hoover Dam and Power plant at a fraction of the cost and impact on the environment when compared to any other means of providing new generation capacity.

### 10.8.2 Low-head hydropower

A low-head dam is one with a water drop of less than 65 feet and a generating capacity less than 15,000 kW. Large, high-head dams can produce more power at lower costs than low-head dams, but construction of large dams may be limited by lack of suitable sites, by environmental considerations or by economic conditions. In contrast, there are many existing small dams and drops in elevation along canals where small generating plants could be installed. New low-head dams could be built to increase output as well. The key to the usefulness of such units is their ability to generate power near where it is needed, reducing the power inevitably lost during transmission.

### 10.8.3 Peaking with hydropower

Demands for power vary greatly during the day and night. These demands vary considerably from season to season, as well. For example, the highest peaks are usually found during summer daylight hours when air conditioners are running. Nuclear and fossil fuel plants are not efficient for producing power for the short periods of increased demand during peak periods. Their operational requirements and their long start-up times make them more efficient for meeting base load needs.

Since hydroelectric generators can be started or stopped almost instantly, hydropower is more responsive than most other energy sources for meeting peak demands. Water can be stored overnight in a reservoir until needed during the day, and then released through turbines to generate power to help supply the peakload demand. This mixing of power sources offers a utility company the flexibility to operate steam plants most efficiently as base plants while meeting peak needs with the help of hydropower. This technique can help ensure reliable supplies and may help eliminate brownouts and blackouts caused by partial or total power failures.

Today, many of reclamation's 58 power plants are used to meet peak electrical energy demands, rather than operating around the clock to meet the total daily demand. Increasing use of other energy-producing power plants in the future will not make hydroelectric power plants obsolete or unnecessary. On the contrary, hydropower can be even more important. While nuclear or fossil-fuel power plants can provide base loads, hydroelectric power plants can deal more economically with varying peak load demands. This is a job they are well suited for.

### 10.8.4 Pumped storage

Like peaking, pumped storage is a method of keeping water in reserve for peak period power demands. Pumped storage is water pumped to a storage pool above the power plant at a time when customer demand for energy is low, such as during the middle of the night. The water is then allowed to flow back through the turbine-generators at times when demand is high and a heavy load is place on the system.

The reservoir acts much like a battery, storing power in the form of water when demands are low and producing maximum power during daily and seasonal peak periods (Fig. 10.14). An advantage of pumped storage is that hydroelectric generating units are able to start up quickly and make rapid adjustments in output. They operate efficiently when used for one hour or several hours.

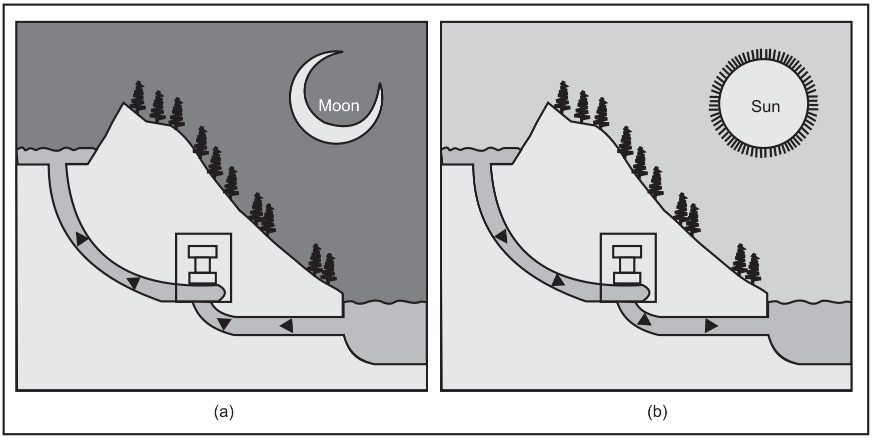



**Figure 10.14** Reservoir acts much like a battery: (a) at night when customer demand for energy is low, water is pumped to a storage pool above the dam, and (b) when demand is high and a heavy load is placed on the system, water is allowed to flow back through the turbine-generators.

Because pumped storage reservoirs are relatively small, construction costs are generally low compared with conventional hydropower facilities.

## 10.8.5 Comparing hydropower to other energy forms

When we hear the term ‘solar energy’, we usually think of heat from the sun’s rays which can be put to work. But there are other forms of solar energy. Just as hydropower is a form of solar energy, so too is windpower. In effect, the sun causes the wind to blow by heating air masses that rise, cool, and sink to earth again. Solar energy in some form is always at work—in rays of sunlight, in air currents, and in the water cycle.

Solar energy, in its various forms, has the potential of adding significant amounts of power for our use. The solar energy that reaches our planet in a single week is greater than that contained in all of the earth’s remaining coal, oil, and gas resources. However, the best sites for collecting solar energy in various forms are often far removed from people, their homes, and work places. Building thousands of miles of new transmission lines would make development of the power too costly.

Because of the seasonal, daily, and even hourly changes in the weather, energy flow from the wind and sun is neither constant nor reliable. Peak production times do not always coincide with high power demand times. To depend on the variable wind and sun as main power sources would not be acceptable to most American lifestyles. Imagine having to wait for the wind to blow to cook a meal or for the sun to come out from behind a cloud to watch television!

As intermittent energy sources, solar power and wind power must be tied to major hydroelectric power systems to be both economical and feasible. Hydropower can serve as an instant backup and to meet peak demands.

Linking wind power and hydropower can add to the nation's supply of electrical energy. Large wind machines can be tied to existing hydroelectric power plants. Wind power can be used, when the wind is blowing, to reduce demands on hydropower. That would allow dams to save their water for later release to generate power in peak periods.

The benefits of solar power and wind power are many. The most valuable feature of all is the replenishing supply of these types of energy. As long as the sun shines and the wind blows, these resources are truly renewable.

The inherent technical, economic and environmental benefits of hydroelectric power make it an important contributor to the future world energy mix, particularly in the developing countries. These countries have a great and ever-intensifying need for power and water supplies and they also have greatest remaining hydro potential. Development is a basic human right, as few would deny. Energy policy makers must meet their responsibility in exploring the most rational options for meeting the energy needs of the developing world, while protecting the environment to the maximum possible extent, for example by limiting greenhouse gas emissions.

## 10.9 Benefits of hydropower

Hydropower provides unique benefits, rarely found in other sources of energy. These benefits can be attributed to the electricity itself, or to side-benefits, often associated with reservoir development. Despite the recent debates, few would disclaim that the net environmental benefits of hydropower are far superior to fossil-based generation. In 2006, for example, it has been calculated that hydropower saved GHG emissions equivalent to all the cars on the planet (in terms of avoided fossil fuel generation).

While development of all the remaining hydroelectric potential could not hope to cover total future world demand for electricity, implementation of even half of this potential could thus have enormous environmental benefits in terms of avoided generation by fossil fuels.

Carefully planned hydropower development can also make a vast contribution to improving living stands in the developing world (Asia, Africa, Latin America), where the greatest potential still exists. Approximately 2 billion people in rural areas of developing countries are still without an electricity supply. As the most important of the clean, renewable energy options, hydropower is often one of a number of benefits of a multipurpose water resources development project. As hydro schemes are generally integrated within multipurpose development schemes, they can often help to subsidise other vital functions of a project. Typically, construction of a dam and its associated reservoir results in a number of benefits associated with human well-being, such as secure water supply, irrigation for food production and flood control, and societal benefits such as increased recreational opportunities, improved navigation, the development of fisheries, cottage industries, etc. This is not the case for any other source of energy.

## 10.10 Characteristics of hydropower

1. Its resources are widely spread around the world. Potential exists in about 150 countries, and about 70 per cent of the economically feasible potential remains to be developed. This is mostly in developing countries.
2. It is a proven and well advanced technology (more than a century of experience), with modern power plants providing the most efficient energy conversion process (>90 per cent), which is also an important environmental benefit.
3. The production of peak load energy from hydropower allows for the best use to be made of base load power from other less flexible electricity sources, notably wind and solar power. Its fast response time enables it to meet sudden fluctuations in demand.
4. It has the lowest operating costs and longest plant life, compared with other large scale generating options. Once the initial investment has been made in the necessary civil works, the plant life can be extended economically by relatively cheap maintenance and the periodic replacement of electromechanical equipment (replacement of turbine runners, rewinding of generators, etc. in some cases the addition of new generating units). Typically a hydro plant in service for 40–50 years can have its operating life doubled.

5. The ‘fuel’ (water) is renewable, and is not subject to fluctuations in market. Countries with ample reserves of fossil fuels, such as Iran and Venezuela, have opted for a large scale program of hydro development, recognising environmental benefits. Hydro also represents energy independence for many countries.

## 10.11 Electrical system benefits

Hydropower, as an energy supply, also provides unique benefits to an electrical system. First, when stored in large quantities in the reservoir behind a dam, it is immediately available for use when required. Second, the energy source can be rapidly adjusted to meet demand instantaneously. These benefits are part of a large family of benefits, known as ancillary services. They include:

1. Spinning reserve—the ability to run at a zero load while synchronised to the electric system. When loads increase, additional power can be loaded rapidly into the system to meet demand. Hydropower can provide this service while not consuming additional fuel, thereby assuring minimal emissions.
2. Non-spinning reserve—the ability to enter load into an electrical system from a source not on line. While other energy sources can also provide non-spinning reserve, hydropower’s quick start capability is unparalleled, taking just a few minutes, compared with as much as 30 minutes for other turbines and hours for steam generation.
3. Regulation and frequency response—the ability to meet moment-to-moment fluctuations in system power requirements. When a system is unable to respond properly to load changes its frequency changes, resulting not just in a loss of power, but potential damage to electrical equipment connected to the system, especially computer systems. Hydropower’s fast response characteristic makes it especially valuable in providing regulation and frequency response.
4. Voltage support—the ability to control reactive power, thereby assuring that power will flow from generation to load.
5. Black start capability—the ability to start generation without an outside source of power. This service allows system operators to provide auxiliary power to more complex generation sources that could take hours or even days to restart. Systems having available hydroelectric generation are able to restore service more rapidly than those dependent solely on thermal generation.

## 10.12 Environmental issues and management for hydropower peaking operations

Hydropower schemes are built on many scales, involve different project types, and play different roles in an integrated energy system. Operating patterns vary, and discharge patterns to the downstream river environment reflect whether the station is operating in base load, peak load or frequency mode.

When meeting base load requirements, a power station usually discharges a constant flow all day and can maintain this for days, weeks and even months depending on the scale of the scheme and the generation needs. When meeting peak load requirements, a power station is turned on at a particular time during the day, generates power at a constant load for a certain number of hours, and is then turned off or set to a different load for another time period, resulting in a high variability in flow discharges. Hydropower stations may also operate in frequency mode, where generators are brought on or off depending on the changing electricity demand throughout the day, essentially 'following' the load.

Many hydropower plants are operated as peak generators or frequency controllers, because they can change their output quickly to follow the fluctuating power demand. A hydropower generating unit can start up or stop within tens of seconds, which provides an important role in an integrated energy system where each type of energy source can be used to its best advantages. Because of its flexibility in generating patterns, hydropower can optimise the efficiency of less flexible fossil or nuclear generation options, and also offers a backup for other more intermittent renewable energy sources such as wind and solar.

Reservoir hydro schemes in particular provide considerable flexibility in energy provision, because with their larger storage they can be operated to provide either base load or peak load services. Run-of-river hydropower schemes provide base load options, but with less flexibility in their ability to provide peak power because of their smaller storage capacities. Pumped-storage plants are particularly well suited to meeting the peaks in electricity demand; they essentially work as a huge storage battery by charging or discharging power according to the system's demand.

### 10.12.1 Potential environmental issues with hydropeaking

Where reservoir hydro schemes are operated primarily to provide peak load services, there are particular environmental risks that should be considered in any environmental impact assessment. With a sound understanding of the potential environmental issues, there are strategies that can be employed at the siting and design stage to minimise or mitigate these risks.

With any hydro scheme, the downstream river environment has an altered hydrograph due to the curtailing of major floods and a flow range restricted to the turbine discharge capacity. For a peaking station, a typical hydrograph shows twice-daily fluctuations from off to full capacity discharges often with weekend shutdowns. A peaking station may show consistent daily to weekly patterns of discharge throughout the year rather than the strong seasonal pattern that might be shown for base load providers, and depending on the scale of the scheme inter-annual variability may be low.

Downstream effects on water quality depend on the storage configuration and offtake depth. If the storage is deep and stratifies and the offtake is low, the downstream environment may experience frequent temperature and dissolved oxygen fluctuations particularly during the summer period, with the power station injecting cold water from deep in the reservoir into the warmer waters of the receiving environment. In situations where there are downstream pollution sources draining into the river system, peaking power station discharges can cause pulses of polluted water downstream rather than a general dilution effect when operating to meet baseload demand.

Downstream effects on the fluvial geomorphology and dominant geomorphic processes differ if a power station is operating to meet base versus peak demand. Major issues with any hydro operations are with the reduced sediment supply to the downstream environment and the erosive capabilities of continuous larger than natural baseflows for baseload operations. With peaking operations, the significant flow discharge patterns affecting the channel form are the rate and frequency of water level rise, the time the station is at its maximum discharge level, and the rate and frequency of water level drop. A rapid increase in water level has considerable bank scouring capabilities. The amount of time the power station discharges at its full capacity influences the degree of saturation of the river banks, which in turn influences the degree of seepage-induced erosion that may occur when the power station turns off. Frequent and rapid drawdowns in water level result in considerable pore water pressures as the water drains out of the banks, so with peaking operations the frequency of seepage-induced erosion events increases, however the severity of any one event may be less than otherwise if the power station has not been on long because the banks will not be as saturated.

Downstream effects on riparian vegetation with any hydro operations can be a loss of species cover and diversity in the riparian zone due to waterlogging and inundation, lack of regeneration and recruitment, and habitat alteration due to bank erosion. Inundation is the submergence of vegetation that prevents gas exchange, and prevents plants carrying out photosynthesis and respiration through their leaves. Waterlogging is the submergence of the root zone, which causes depletion of oxygen in the soil and prevents respiration by plant roots. Light limitation is also a stress because plants require adequate daylight hours without inundation or waterlogging to acquire carbon through photosynthesis. With peaking operations there are reduced risks of impact due to waterlogging and inundation, as the riparian zone is drained and exposed to sunlight on a daily basis. However there is still the case of limited regeneration and recruitment, because seedlings cannot establish on the banks where water levels rise rapidly several times per day and wash them away. Banks close to the power station may eventually end up with a high percentage cover of mineral substrates, and riparian tall woody shrub species may be replaced with ephemerals such as grasses, gramonoids (grass-like plants) and tolerant semi-aquatic herb which may provide some structural stability to river banks.

Downstream effects on macroinvertebrates (e.g. aquatic insects and micro-crustaceans) for any hydro operations are often a reduction in species diversity and abundance, as well as loss of edge and snag habitat. The significant drivers of these impacts are that the water levels with the power station off are often lower than mean summer baseflows resulting in less habitat availability for colonisation, and water levels with the power station on are often higher than mean winter baseflows resulting in greater depths and current velocities than optimal for some species. With peaking operations, water levels change across this range several times per day, and frequent water level as well as temperature changes would cause high stresses on the instream biota. For example, high shear stresses, that is the force applied to the river bed from rapidly rising water levels, is associated with faunal displacement and possibly bed movement under rapidly varying flows.

Hydropower schemes can affect migratory aquatic species due to the physical barrier to upstream migration presented by the dam itself. Baseload discharge patterns can reduce fish populations in the downstream environment due to reduced macroinvertebrate food supplies, loss of snag habitat, and impacts on spawning and migration cues due to changes in the seasonality of flows (and in cases temperature). Where there are natural downstream obstacles to fish migration such as river gorges, baseload discharge patterns may cause fish migration difficulties due to sustained high flow releases, whereas peaking discharge patterns may provide more frequent opportunities for migration through these gorges. Social issues can also arise due to peaking operations, for example human safety issues with rapidly changing water levels, risks of stock strandings, and issues with pump setups for landowners.

### 10.12.2 Investigating environmental impacts due to hydropeaking

Investigations of environmental impacts of hydropeaking operations must be underpinned by a sound analysis of operating patterns and downstream hydrology. The drivers of impact in the downstream environment are the rapid changes in flow, and at any given point in the system this will result in different water heights, current velocities, degree of backwater inundation or channel dewatering, ramp-up and drawdown rates. A detailed set of gauging sites and water level recorders will provide basic data that can then be fed into a hydrological model of the river system to assist in modelling of environmental impacts. Because of the rapid changes in water level with peaking operations, water quality impacts are best assessed using sites that continuously record temperature, dissolved oxygen and conductivity, at several sites downstream of the power station. Sites should be in conjunction with a gauging or water level station so that readings can be related to flow/level changes, and ideally upstream and downstream of significant tributaries. Investigations of the impacts of peaking operations on fluvial geomorphology require particular attention because the dominant geomorphic processes can vary considerably depending on the type of discharge regime from the power station. These investigations can employ a number of different approaches. Development of a sediment budget for the downstream environment provides a valuable framework for more detailed reach-specific assessments, as does mapping of riverbank and bed attributes using a hand-held GPS to identify those zones most susceptible to bank erosion. For existing schemes, broadscale geomorphic change in over time can be assessed using comparative aerial photography. Changes to channel profile, depth and channel geometry can be assessed using repeat survey cross-sections. Changes to bank stability and profile can be assessed using erosion pins and photo monitoring. Scour chains in association with erosion pins offer the ability to show maximum scour that occurred during the period between erosion pin measurements. Water samples analysed for suspended sediment concentrations at different points in the river, particularly with continuous autosamplers, are valuable where rivers transport fine-grained sediments.

Further techniques can be employed for predicting the fluvial geomorphic impacts of peaking operations for proposed hydropower projects. Sediment transport capacity of the flow regime can be assessed with dedicated experiments and hydraulic calculations requiring good particle size data and hydraulic characteristics at a cross-section. Penetrometer readings of sediment banks can provide an indication of bank cohesion and strength. Piezometers are a valuable tool to determine groundwater changes in the near river sediment banks in response to changes in river level, so that degree of bank saturation, pore water pressures and degree of risk of draw-down seepage induced erosion can be assessed, often with the aid of computer models. Close investigation of the inter-relationships of riparian vegetation composition and cover with bank stability processes is essential in any investigations.

Investigations of the impacts of peaking operations on riparian vegetation require a basic broadscale mapping exercise of riparian plant communities, and more site-specific surveys of cover and abundance of plant species using a quadrant based approach. Quadrants need to be located in a profile up the bank so that they can be related to different water levels and inundation times. Additional riparian vegetation investigations should encompass assessments of recruitment within each survey quadrant, sampling and analysis of root mat densities in different bank sediment types, and assessment of the contributions of mosses or ground cover species to stream bank stability.

For assessment of hydropeaking impacts on macroinvertebrate populations, investigations should consider species presence/absence, species abundance, habitat availability and shear stress. Several techniques exist to obtain samples for identification. A rapid presence/absence assessment can be undertaken using kick-net sampling in riffles, with samples identified to the family level, and ideally this data would be fed into a predictive bioassessment model which can compare observed taxa to expected taxa and thus provide a rating of degree of impact. Considerable work must go into the development of a bioassessment model if no appropriate model exists. Macroinvertebrate abundance can be assessed using quantitative (surber) samples that are typically identified to genus level, and in cases to species level to identify any threatened species.

Habitat availability analyses requires two data sets—hydraulic data (e.g. velocity, depth, substrate characteristics) collected in field surveys from representative transects across the river under power station on and off conditions, and habitat preference data for key aquatic taxa derived from either the literature and/or from field sampling—to derive plots of ‘weighted usable area’ for different flow levels. Finally, shear stress analyses can be undertaken in the field by placing hemispheres of known densities on the stream bed and observing their movement under changing flow conditions, an exercise that requires diving and so safety is a prime consideration when considering this technique.

Assessment of the impacts of peaking operations on fish species are largely based on field fish surveys. Backpack electrofishing is often chosen as a standard sampling method. It allows for a repeatable approach with minimal mortality rates, has known biases, and offers a method of comparison between sites. Results can be standardised into a comparative Catch Per Unit Effort figure for each visit to each site, and site ordination. Habitat availability and preference should also be undertaken as per the macroinvertebrate assessments. Site selection should include significant tributary streams as well as the mainstem river, and particular attention paid in sampling program design to upstream and downstream of natural flow obstacles to migration such as gorges. It can be valuable to dissect some fish to analyse their food sources, to better enable linkages in fish condition to be made with macroinvertebrate populations. More specific assessments are likely to be required for significant species such as waterbirds or aquatic mammals, which would vary considerably in different parts of the world.

### 10.12.3 Environmental management and mitigation measures for hydropeaking

A range of management approaches and mitigation measures can be employed to address the potential environmental issues with peaking operations, and investigations of impacts should be directed at identifying and evaluating management options as much as assessing impacts.

#### *Discipline-specific options and objectives*

*(a) Water quality*

1. Storage siting and design should consider whether reservoir stratification is likely to occur, and whether a multi-level offtake may be required to ensure release of oxygenated and ambient temperature water.
2. Air injection in the turbines can ensure sufficient oxygenation of water releases.
3. Siting upstream of a significant tributary can ensure mixing of power station discharges with water of ambient temperatures to the further downstream environment.

*(b) Geomorphology*

1. Physical buttressing of riverbanks.
2. Reduction of the maximum power station discharge to reduce the phreatic surface gradient in the banks.
3. Minimising the duration of maximum discharges to reduce the extent of bank saturation.
4. Maintenance of a minimum environmental flow to lessen scour of the bank toes and reduce phreatic surface gradient.
5. Measures that would increase the viability of riverbank vegetation.

*(c) Riparian vegetation*

1. Instigating low flow rates for three summer months every year to allow riparian plants to grow and reproduce and for recruitment to occur during the season of greatest metabolic activity.
2. Ensure 24–48 hour shutdowns on approximately a weekly basis to reduce stresses of waterlogging and inundation (note this would likely occur anyway with peaking operations).
3. Facilitate regeneration by direct-seeding of the river banks with local riparian species.
4. Measures that would improve physical stability of the riverbanks.

*(d) Macroinvertebrates*

1. A minimum flow to ensure that a proportion of the channel is permanently inundated, that snag habitats on the channel margins are inundated, and that the channel can maintain a constant macroinvertebrate community when the power station is not discharging.
2. Management of rates of increase and decrease of power station discharge can slow the rates of downstream river level changes, and thus reduce shear stresses on the bed particularly on the rising limb of the hydrograph by reducing water surface slopes, and reduce incidences of stranding of fish and macroinvertebrates.

*(e) Fish*

1. A minimum environmental flows would benefit macroinvertebrate communities and so would indirectly benefit fish that feed on the macroinvertebrates.
2. A partial or stepped ramp-down would provide cues to the fish of dropping flows before full dewatering of habitats occurred, hence reducing the potential for fish stranding under peaking operations.
3. Restocking with native species.

## *Options assessment*

A number of the management and mitigation options to address environmental impacts of peaking operations involve dedicated water release patterns. Water management options include minimum environmental flows, power station ramp-downs, power station rates of flow increase, reducing maximum discharges, and minimising durations of full gate discharges.

Controls on patterns of release to the downstream environment to address potential impacts to the downstream ecosystem can be provided either through the power station discharges, through a dedicated release valve or by a re-regulating structure downstream of the power station.

In general, water management options constitute significant constraints on power station operations and can incur considerable losses in generating potential. Large generating turbines may not be able to generate small discharges required for minimum environmental flows, and many have rough running bands that should be largely avoided. For delivery of an environmental flow, an upfront major capital cost may be preferable to ongoing constraints on discharge patterns. If the siting allows it and the cost-benefit analysis supports it, construction of a re-regulation storage to allow downstream release patterns to be dedicated to environmental management outcomes can be very successful. A re-regulating structure is a dam or weir that impounds the regulated flows from the power station, and allows control over release patterns to downstream of the structure. Mini-hydro turbines can also/alternatively be employed to recover generating capability with minimum flow releases.

A ramp-down or step-down rule for the power station could be compatible with peaking operations. This would be particularly of benefit in reducing seepage-induced erosion in riverbanks, and would also offer benefits to fish to reduce risks of fish strandings.

Ramping up constraints would not be desirable with peaking operations, as they would reduce the rapid start advantage that the hydropower station offers with the provision of peak load. The provision of a minimum environmental flow can lessen the need for a ramp-up rate, as it would ensure that shear stresses are reduced as water levels rise in the downstream river system.

Depending on the circumstances, it is likely that several of the options are utilised as a package. Water management options in combination with localised treatment works can be successful. Localised treatment options include bank protection works, bank revegetation works, local willow control, and fencing/stock exclusion. There may also be site-specific opportunities, such as diversion of part of the downstream flow to lessen the degree of water level rise and fall.

To sum up, there are a number of potential environmental issues associated with hydropeaking operations, as well as a range of mitigation measures available to substantially address these issues. Potential environmental issues should be thoroughly assessed prior to finalising the siting and design for a proposed scheme, so that potential impacts can be minimised, and that the scheme can include any mitigation or management measures as part of its design. Many of these measures can also be employed to minimise impacts arising from peaking operations with an existing scheme. Assessment of management measures should consider any possibilities of trade-offs that might arise amongst the different ecosystem components, and should be subject to a thorough cost-benefit analysis.

# 11
# Small hydroelectric plants

## 11.1 Introduction

Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. For generations water has been used as a source of energy by industry and by a limited number of utility companies. In the continental United States, most rivers and streams capable of producing huge amounts of hydroelectric power have been harnessed; however, this does not preclude the possibility of using mini-hydroelectric power as a source of energy supply for home or farm. Harnessing a stream for hydroelectric power is a major undertaking. Careful planning is necessary if a successful and economical power plant is to result. State water laws and environmental concerns must be determined.

Precise field data must be gathered to compare the amount of power that can be expected from a hydroelectric installation to the electrical requirements of the home or farm. Then detailed plans that consider both construction and maintenance can be drawn up. Perhaps the greatest mistake made when considering small hydroelectric installations is the overestimation of a proposed plant's capability. This chapter bulletin will help to start the planning of a small power plant on a given stream of water. One of the first steps in planning is to measure the power potential of the stream. The amount of power that can be obtained from a stream depends on:

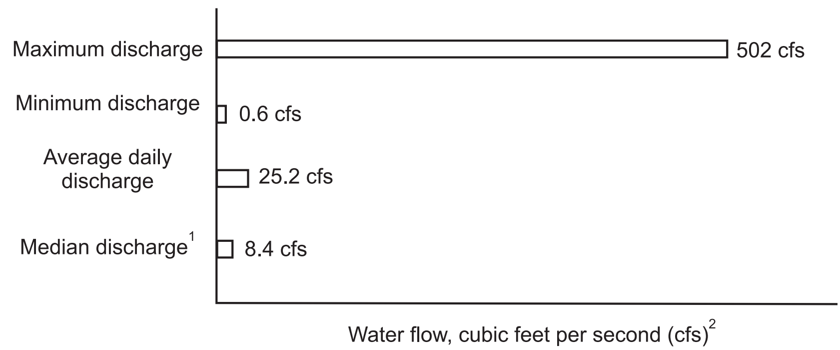
1. The amount of water flow.
2. The height which the water falls (head).
3. The efficiency of the plant to convert mechanical energy to electrical energy.

## 11.2 Stream flow

Stream flow varies greatly from season to season and depending on the nature of the terrain. A typical discharge from a 22 square mile hilly to mountainous drainage area in the Northeast during a year of normal precipitation is summarised in Fig. 11.1. The smallest commercially manufactured hydroelectric power plant at one-half kilowatt (kW) or 500 watts needs 1.1 cfs with a 12′ height of water fall or head. Therefore no power can be generated during low-flow periods without reservoir storage. It is also interesting to look at the peak flow. A ten-kilowatt hydroelectric plant needs 16.3 cfs with a 12′ head, leaving a substantial part of the peak flow to be contended with—not a simple task. This extreme variation illustrates the value of a reservoir to regulate and even the flow.

## 11.3 Measuring flow

Two methods are commonly suggested for measuring the flow in small or medium sized streams. Large discharges are best determined by a hydraulic engineer. The float method of testing stream flow is the easiest test to conduct and will yield satisfactory data, except in cases where a stream is shallow or rocky and thus impedes the movements of a weighted float.




[1]Flow is 8.4 cfs or less for 183 days or half the year.

[2]1 Cubic foot per second = 449 gallons per minute.

**Figure 11.1** Stream flow

Basically the cross section of an unobstructed area of the stream is measured and a weighted float such as a bottle weighted with pebbles is timed as it floats down a 100 foot course.

The weir method is more time consuming but may be the most satisfactory test if the stream is very small, shallow, rocky, obstructed, or if there is an existing dam (Fig. 11.2). A weir is a dam with an opening or notch through which the entire stream flows. The flow may be calculated by precisely measuring the depth of water flowing over the crest of the weir. Tongue and groove planking makes a good temporary weir for streams not more than 1 or 2 ft deep and 6–10 ft wide. The selected references give more detail on how to measure stream flow by the weir or float method. No matter what method of flow measurement is used, it is very important to measure stream flow many times over a year or more (Fig. 11.3).

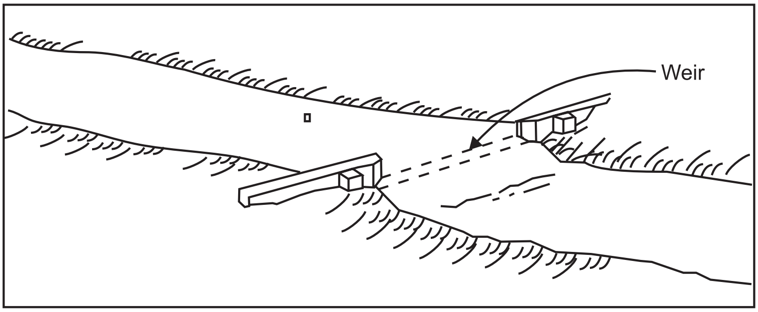



**Figure 11.2** Measuring flow with a weir

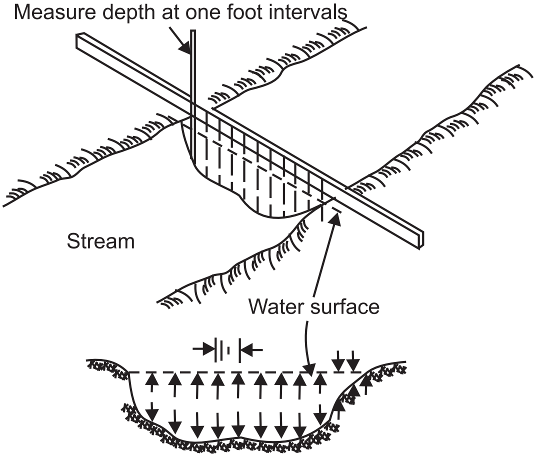
## 11.4 Dams

Water must fall in order to generate power from a stream. In most cases the fall is enhanced and increased by constructing a dam which creates a head (Head is the vertical distance from the surface of the water at the dam down to the water in the stream below where the turbine is located). The higher the dam or head, the greater the power a given amount of water will produce. A dam also provides a storage basin to regulate stream flow and thereby increases power potential.

Before pursuing dam construction further, you should consider these points:

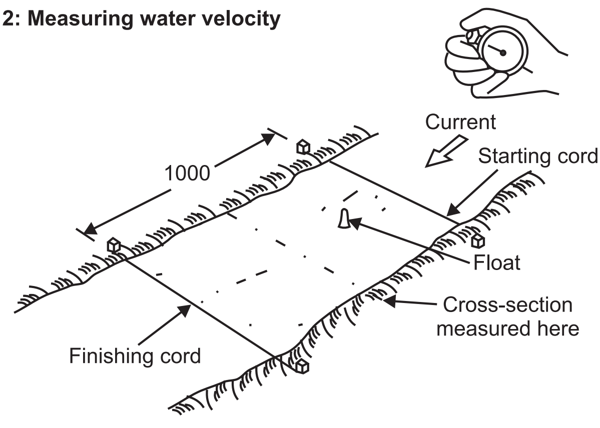
1. The construction of a dam is a highly technical undertaking. You need to collect extensive field data to choose the best site and design a safe dam. A professional engineer can best advise you on construction of a safe dam for your particular site.
2. Find out what permits are required if a stream is to be impounded. Laws vary from state to state: some are lenient; some are very stringent. Your state environmental conservation office should be able to supply you with the necessary information.
3. Be aware that you must control all land to be flooded.

**Step 1: Measuring cross-section area**




$$\text{Average depth} = \frac{\text{Sum of measured depths}}{\text{\# Intervals measured}}$$

**Step 2: Measuring water velocity**




**Step 3: Calculating flow rate**

The flow rate is calculated by the formula:

$$Q = 0.83\left(\frac{bd}{144}\right)\left(\frac{100}{t}\right)$$

Q = flow rate, cubic feet per second
b = stream width, inches
d = average stream depth, inches
t = time for float to drift 100 feet, seconds

**Figure 11.3** Measuring flow with a float

4. In the event of dam failure, you will be responsible for all downstream damage. Your insurance underwriter may be able to advise you on the availability of liability insurance.
5. You must respect the rights of others to stream use outside of your property.
6. You may be faced with resistance from nearby landowners and conservation-minded groups or individuals.
7. Obtain solid cost estimates for the dam construction. Costs vary widely, depending on the particular site, but it is reasonable to assume that the construction of any worthwhile dam will run to several thousand dollars. Will the capital outlay for construction be justified by the long-term benefits of an installation?

Figure 11.4 shows the hydroelectric installation with reservoir.

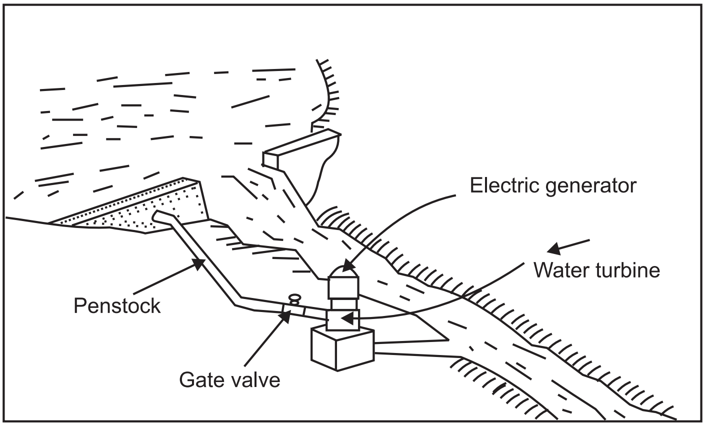



**Figure 11.4** Hydroelectric installation with reservoir

## 11.5 Diversions

Because legal requirements and high costs restrict new dam construction, other methods of water development may be more suitable. In some places only a round concrete box structure is needed to divert part of the flow of a stream through a pipe to a downstream turbine (Fig. 11.5).

On any given stream, the best site for a diversion is usually quite obvious: a natural waterfall, a swift current or a steep slope. The terrain should be steep enough (10 per cent slope or more) so the diversion pipe doesn't have to be too long to obtain sufficient head. Because a diversion has no backup storage for periods of low flow, potential power is sometimes calculated by determining the runoff in a year of normal rainfall which is exceeded on half the days of the year. The example watershed has a stream flow of 8.4 cubic feet per second or less for half the year. With a 12” head, this stream can operate a 5 kW generator at full capacity for half the year and at about 50 per cent capacity for the remainder. Some people install batteries to provide electrical storage for periods of low flow.

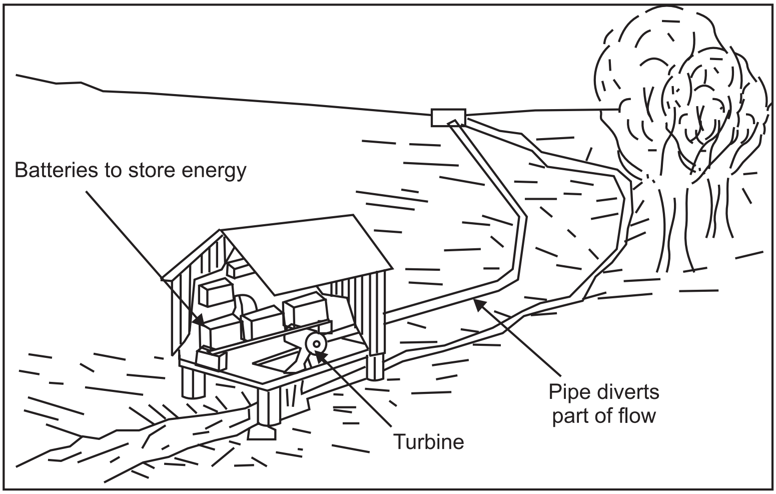



**Figure 11.5** Diversion

## 11.6 Measuring head

After the height of the water behind the proposed dam or diversion has been decided, it is necessary to measure the head of water that will result. To determine the difference in level between two points, set a surveyor’s level about midway between the points. Have an assistant hold a surveyor’s rod at one point, sight through the level and record the height reading on the rod. Move the rod to the second point and read. The difference of the readings is the difference in elevation of the two points (Fig. 11.6).

Often it is impossible to see the two points from a single setting of the level so rods must be read at intermediate or turning points. The differences in readings between each pair of points can be added together to calculate the total elevation drop from the dam or diversion.

## 11.7 Calculating power

Power output, in kilowatts is calculated by the formula:

$$kW = 0.0846 \times E \times Q \times H$$

where, Q = Water flow, in cubic feet per second
H = Head, in ft.
E = Efficiency of hydroelectric plant, per cent divided by 100.

Friction, generator losses and turbine losses reduce the efficiency of a power plant. Small plants are about 40 per cent efficient. Five to ten kilowatt plants may be 60–70 per cent efficient when operating at full capacity. For initial estimates, calculate power based on 50 per cent efficiency.

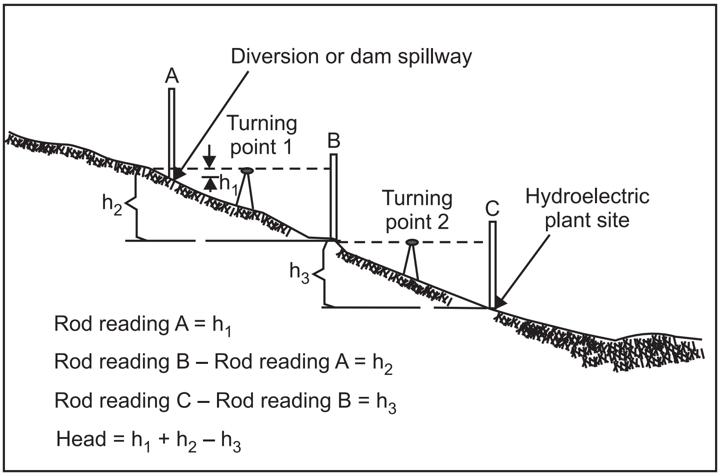



**Figure 11.6** Measuring head

Table 11.1 lists the water flow and head needed to run various small hydroelectric plants operating at 50 per cent efficiency. Manufacturers of hydroelectric plants also list power outputs of their units at various flows and heads.

**Table 11.1** Required water flow and head for small hydroelectric plants.

| **Generator output, kilowatts**[1] | **Head (ft)** | | | | |
|---|---|---|---|---|---|
| | 10′ | 20′ | 50′ | 100′ | 200′ |
| | Water flow, cubic feet per second | | | | |
| 0.5 | 1.2 | 0.6 | 0.24 | 0.12 | 0.06 |
| 1 | 2.4 | 1.2 | 0.5 | 0.24 | 0.12 |
| 2 | 4.7 | 2.4 | 0.9 | 0.5 | 0.24 |
| 5 | 11.8 | 5.9 | 2.4 | 1.2 | 0.6 |
| 10 | 23.6 | 11.8 | 4.7 | 2.4 | 1.2 |

[1] overall hydroelectric plant efficiency is 50 per cent.

## 11.8 Components

### 11.8.1 Penstocks

Friction in the pipe (penstock) or open channel that carries water to the generator is another cause of power loss. Most small hydroelectric sites have a small or moderate head, so it is very important to use large penstocks to reduce losses.

If you are diverting a water source far up the hill, plastic or aluminium irrigation pipe and the heavier walled, pressure rated PVC plastic pipe make good penstocks. Table 11.2 shows head losses for typical plastic pipe. The flow rates to the right of the dashed lines have velocities that exceed 5–7 ft/s and are not recommended. Use a larger pipe instead.

For example, Table 11.1 shows a 2 kW generator requires 0.6 cfs with a 100-foot head. Three hundred feet of 3” PVC pipe carrying 0.6 cfs from an upstream diversion has a head loss of 3 × 10.2 = 30.6 ft. Thus the diversion must be 100 + 30.6 = 130.6 feet above the generator to compensate for the friction or head loss in the pipe. A 6” pipe has only a 0.54 × 3 = 1.62 ft head loss.

**Table 11.2** Head loss for plastic pipe.

| Nominal pipe diameter | Inside diameter | Flow rate, cubic feet per second1 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.8 | 1.0 | 2.0 | 4.0 | 6.0 | 8.0 | 10.0 |
| | | Head loss, feet per 100 feet of pipe | | | | | | | | | | | |
| **160# PVC plastic pipe** | | | | | | | | | | | | | |
| 2” | 2.193” | 2.44 | 8.22 | 18.7 | | | | | | | | | |
| 3” | 3.230” | 0.37 | 1.34 | 2.84 | 4.83 | 10.2 | | | | | | | |
| 4” | 4.154” | 0.11 | 0.39 | 0.83 | 1.42 | 3.01 | 5.12 | 7.74 | | | | | |
| **80 psi plastic irrigation pipe** | | | | | | | | | | | | | |
| 6” | 5.900” | – | 0.07 | 0.15 | 0.26 | 0.54 | 0.93 | 1.40 | 5.06 | | | | |
| 8” | 7.840” | – | – | – | 0.06 | 0.14 | 0.23 | 0.35 | 1.27 | 4.58 | 9.70 | | |
| 10” | 9.800” | – | – | – | – | – | 0.08 | 0.12 | 0.43 | 1.54 | 3.27 | 5.58 | 8.42 |
| 12” | 11.760” | – | – | – | – | – | – | 0.05 | 0.18 | 0.64 | 1.35 | 2.29 | 3.47 |

[1]One cubic foot per second = 449 gallons per minute

### 11.8.2 Trash racks and head gates

Even small streams can become torrents carrying large trees and other debris. Plan to protect the generator and water passages from debris by installing a trash rack at the head of the penstock. Set steel bars on edge to the flow of water and space about 1” apart. Normally trash racks are set on an incline to increase area so water velocity is less than 1.5 ft/s through the rack. An inclined rack is easier to clean with a rake. This feature is particularly important in the fall because leaves may blanket a rack in an hour or two. A head gate or valve should be installed below the trash rack to control flow and to allow the turbine to be inspected and repaired.

### 11.8.3 Turbines

The towering water wheel driving the old mill's grinding stones creates a romantic image, but it is too slow and ponderous to efficiently convert water power to electric power. For example, a 5 ft diameter wheel that is 16" wide will generate only 300 W or less. A compact turbine and generator is a better choice unless you are renovating an old mill site. Hydroelectric plants are available in capacities ranging from 0.5 to 12 kW. A reaction turbine, either the Francis type or propeller wheel type, is turned by a mass of water falling through a duct encasing a wheel. Reaction-type generators are good choices if you have ample water supply but a low head. A reaction wheel is subject to greater friction losses than an impulse wheel; however, it has greater flexibility in installation (Fig. 11.7).

An impulse (Pelton) turbine turns by the velocity of a jet of water striking the turbine's wheel cups and can operate on as little as 1.5 cfm of water. In order to be most effective, a head of at least 50" is required (Fig. 11.8). The type of facility you wish to provide with electrical service will largely determine whether you use an alternating or direct current generator. Lights and the universal motors that operate small appliances and tools will operate on DC. Large motors, TVs and many appliances require AC to operate. Alternating current may be transmitted greater distances and on smaller wires than is possible with direct current; however, an AC installation does require an extra investment in governing equipment. Direct current generators are usually less expensive than AC generators but they do require expensive inverters to convert to AC. The potential of storing DC in batteries during low-usage periods and at times of uneven water flow is a compensation of such a system.

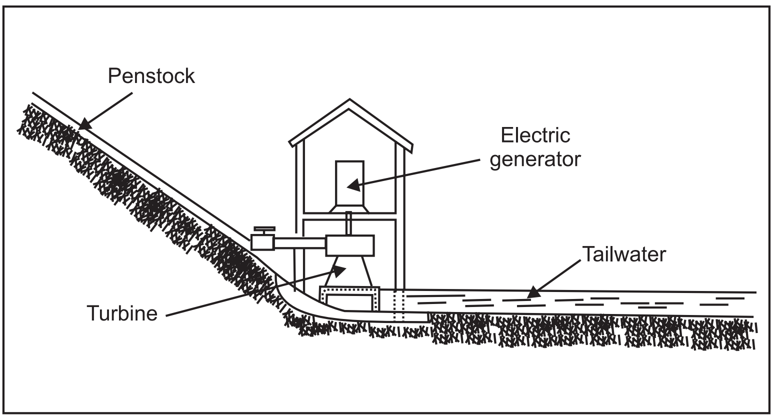



**Figure 11.7** Reaction turbine

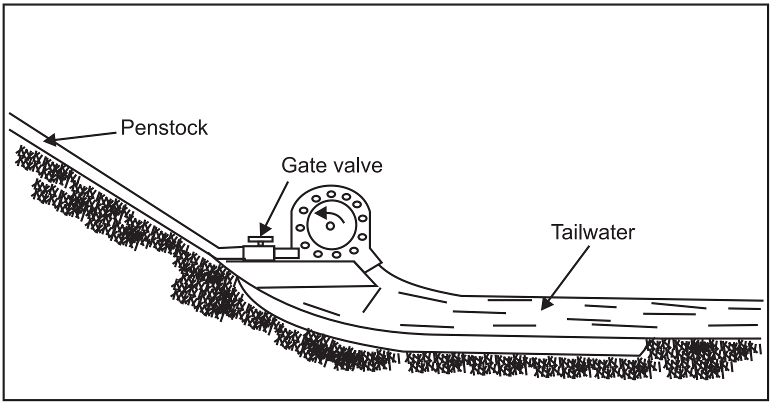



**Figure 11.8** Impulse turbine

## 11.9 Causes of failure

The main reasons for lack of success with small water power developments are:

1. Failure to realise how important full field data is for proper design.
2. Failure of home-made equipment made with junked parts.
3. Overestimating the amount and constancy of the stream flow.
4. Penstocks or flumes, which are too small to allow the plant to operate at full capacity.
5. Failure to anticipate the expense of keeping trash racks clear and machinery in good repair.
6. Failure to design and plan for winter ice buildup.
7. Overestimation of a proposed plant's capability. The average home has demand peaks varying from 4 to 12 kW.

# 12

# Hydropower development in India

## 12.1 Introduction

India has immense economically exploitable hydropower potential of over 84,000 MW at 60 per cent load factor (1,48,700 MW installed capacity), with Brahmaputra, Indus and Ganges basins contributing about 80 per cent of it. In addition to this, small, mini and micro hydropower schemes (with capacity less than 3 MW) have been assessed to have 6781.81 MW of installed capacity. Of this enormous hydro potential, India has harnessed only about 15 per cent so far, with another 7 per cent under various stages of development. The remaining 78 per cent remains unharnessed due to many issues and barriers to the large scale development of hydropower in the subcontinent.

Various studies have established the ideal hydro:thermal power mix for India at to be at 60:40. The present mix of 75:45 is creating much problem in the Indian power system with country facing energy shortage of 9.3 per cent and peaking shortage of 12.8 per cent. The total requirement ending XI plan is set to be 2,06,000 MW. The current installed thermal and hydropower capacity stands at 66 and 26 per cent of the total power generated with 83,272 and 32,726 MW respectively. Remaining 8 per cent of 10,091 MW is achieved from other forms including wind and nuclear. The current captive generation amounts to 14,636 MW.

India's power system is divided into five major region namely, the Northern region, Western region, Southern region, Eastern region and North–Eastern region, with each region facing separate issues. While the Eastern and North–Eastern regions are power abundant, the Northern and Western regions have greater power demands. The hydropower potential is largest in NE region with 98 per cent of it still untapped. Northern, Eastern, Western and Southern regions have 79, 77, 23 and 33 per cent untapped hydropower potential respectively (Table 12.1).

The Central Electricity Authority (CEA) and Ministry of Power (MoP) are the nodal agencies involved in power sector planning and development at the central level. Being a concurrent subject under the Indian Constitution, electricity is generated, transmitted, maintained and developed both by central and state authorities, with the primary role with the states. With the central policy providing the overall direction for development, state determines the power generation, distribution and management systems. The development of water resources lies with the state government. Since hydropower development involves water resources, the responsibility of its development stays primarily with the state agencies.

**Table 12.1** List of hydro electric stations with capacity above 3 MW.

| Region | No. of stations | No. of units | Capacity (MW) |
|---|---|---|---|
| Northern | 78 | 234 | 11,070.30 |
| Western | 45 | 117 | 6588.80 |
| Southern | 92 | 386 | 11,004.35 |
| Eastern | 26 | 82 | 2424.10 |
| Northeastern | 15 | 42 | 1094.70 |
| Total | 256 | 761 | 32,182.25 |

The power sector in India is still largely public with 89 per cent share in the total installed capacity.

## 12.2 Reforms in the electricity sector in India

With the liberalisation of the economy, the government of India has been encouraging and invited private sector for investment in the power sector. Accordingly, a conducive policy environment has been created by modifying the Electricity Act. The new Electricity Act–2003 deals with the laws relating to generation, transmission, distribution, trading and use of electricity. The Act has specific provisions for the promotion of renewable energy including hydropower and cogeneration. It has been made mandatory that every state regulatory commission would specify a percentage of electricity to be purchased from renewable by a distribution licensee. The National Electricity Policy announced in 2005 aims at access of electricity by all households and per capita availability of electricity to be increased to 1000 units by 2012.

The policy underlines that renewable energy potential needs to be exploited and private sector would be encouraged through suitable promotional measures. Regarding fixing of tariff, the government has announced Tariff Policy in 2006 wherein the State Regulatory Commissions are required to fix tariff in their respective state and also decide about the renewable purchase obligation. The Electricity Act and Tariff Policy are favourably tilted towards increasing power generation from renewable. Now, Central Electricity Regulatory Commission has also announced the tariff calculation guidelines for renewable technologies including for small hydro projects.

The existing power deficit and a rapid growing demand coupled with government commitment to provide access to electricity for all has necessitated a large scale capacity addition program. A capacity addition of 78,000 MW in the 11th Plan (2007 to 2012) and approximately one 1,00,000 MW in the 12th plan (2012–2017) is planned. Concurrent investments in transmission and distribution are also going on.

Such a gigantic task is strongly supported and complemented by the private sector. These changes facilitated the removals of barriers to investment, improved the functioning of the system and resulted in additional generation of power much in excess of that achieved in the earlier plans. Ministry of new and renewable energy (MNRE) government of India is the nodal ministry for small hydropower development in India.

## 12.3 Government of India (GOI) policy on hydropower development

Despite hydroelectric projects being recognised as the most economic and preferred source of electricity, the share of hydropower in our country continued declining since 1963. The hydro share declined from 50 per cent in 1963 to about 25 per cent in 2010. For grid stability the ideal hydrothermal mix ratio for Indian condition is 40:60. In order to correct the hydrothermal mix to meet the grid requirements and peak power shortage, in August, 1998 and thereafter in Nov. 2008, the government of India announced a Policy on 'hydropower development'. Project affected people have been made long term beneficiary stakeholders in the hydro projects by way of 1 per cent of free power with a matching 1 per cent support from state government for local area development thus ensuring a regular stream of benefits. An initiative of installing 50,000 MW large hydro projects in the country was announced by the government. By 1998 small hydropower projects established themselves as a techno economically viable option for generating power with some preferential treatments.

Encouraged by the growing private sector participation in the sector and the potential of SHP projects to meet power requirements of remote and isolated areas, where grid extension is relatively expensive, small scale hydro was identified as an area to provide thrust in the overall hydropower development of the country. This led to transfer of the subject of hydro up to 25 MW from Ministry of Power (MOP) to MNRE in December 1999.

The process of reforms is an ongoing one and government of India has been vigorously pursuing this path for the past five to six years. Hydropower is a renewable source of clean energy and is used to supplement the base load provided by thermal power plants and storage for wind energy through pumping. To enable the project developer in the hydro sector a reasonable and quick return on investment, merchant sale of up to a maximum of 40 per cent of the saleable energy has been allowed.

Central Electricity Authority (CEA) has issued various hydroelectric related reports and guides are available through web. Some of them are the best practices in hydroelectric generation; preliminary ranking study of hydroelectric scheme; guidelines for accord of concurrence of HE scheme; guidelines for formulation of DPRs for HE scheme; draft model contract document for hydro projects; project monitoring status reports; project clearance status reports and Status of 50,000 MW hydroelectric Initiative reports. The 12th five-year plan also suggests that for projects held up for environment and forest problems, efforts may be made by the concerned state government/developer to get the timely E&F clearances. Problems such as local agitation (law and order), land acquisition, etc. need to be resolved by the concerned state government. Tendency of converting storage projects (as identified by CEA) to run-of-river projects should be discouraged. Project developer should seek long-term open access by indicating at least the region(s) in which they intend to supply their power to enable development of transmission system.

## 12.4 Hydropower class

There is no worldwide consensus on definitions regarding SHP, mainly because of different development policies in different countries. Based on installed capacity of hydropower projects, classification of hydropower varies differently in various countries. A general classification may be taken as:

| | |
|---|---|
| Pico | 5 kW and below |
| Micro | 100 kW and below |
| Mini | 2000 kW and below |
| Small | 25,000 kW and below |
| Medium | 1,00,000 kW and below |
| Large | Above 1,00,000 kW |

India has a history of about 110 years of hydropower. The first small hydro project of 130 kW commissioned in the hills of Darjeeling in 1897 to mark the development of hydropower in India. At Present the biggest capacity plant is a run of river Naptha Jhakri Hydro project of 1500 MW in Himachal Pradesh. Development of hydropower resources is important for energy security of the country. It takes about 10 years for developing a large-scale hydro project, from planning to commissioning. The hydropower development is greatly boosted with the hydropower policy announcement in 1998 and again in 2008. Advance action on the identified hydro electric schemes need is being taken during 11th Plan (2007–12) period itself as long period is required for development of detailed project reports (DPRs), obtaining various clearances like environment and forest clearances and CEA clearance, investment decision and achieving financial closure. It has been proposed to maximise hydro capacity addition during 12th plan (2012–17) for reducing $CO_2$ emissions and energy security of the country. A shelf of 109 hydro electric schemes aggregating to 30,920 MW has been identified.

## 12.5 Small hydropower development

### 12.5.1 Grid-based SHP

Beginning of the 21st century saw near commercialisation in the small scale hydro sector. There are 760 small hydro projects in India with total installed capacity of 2820 MW. The MNRE decided that out of the total grid interactive power generation capacity that is being installed, 2 per cent should come from small hydro. This translates to about 1400 MW capacity addition during 2007–2012. A target of 3000 MW for the 12th from small hydro has been fixed and to increase capacity addition of about 500 MW per year. The present focus of the SHP program is to lower the cost of equipment, increase its reliability and set up projects in areas that give the maximum advantage in terms of capacity utilisation. SHP projects are being set up both in public and private sector.

Today the SHP program in India is essentially private investment driven. 228 private sector SHP projects of about 1230 MW capacity have been setup. Private sector entrepreneurs are finding attractive business opportunities in small scale hydro.

The MNRE is giving financial subsidy, both in public and private sector to set up SHP projects. In order to improve quality and reliability of projects, it has been made mandatory to get the project tested for its performance by an independent agency and achieving 80 per cent of the envisaged energy generation before the subsidy is released. In order to ensure project quality/performance, the ministry has been insisting to adhere to IEC/International standards for equipment and civil works. The subsidy available from the Ministry is linked to use of equipment manufactured to IEC or other prescribed international standards.

### 12.5.2 Decentralised SHP

The rural energy scenario in India is characterised by inadequate, poor and unreliable supply of energy services. Realising the fact that small scale hydropower projects can provide a solution for the energy problem in rural, remote and hilly areas where extension of grid system is comparatively uneconomical, promoting small scale hydro projects is one of the objectives of the small hydropower program in India. A number of mini/micro hydro projects have been set up in remote and isolated areas, mainly in Himalayan region. While these projects are developed by various state agencies responsible for renewable energy, the projects are normally maintained with local community participation. A number of tea garden owners have also set up such micro hydro projects to meet their captive requirement of power. Isolated grid often faces the problem of poor plant load factor and making financial return difficult for the plant. But this provides opportunities for the area to have industry expansion, cottage or small industry, irrigation pumping, drinking water, agro and other application, education and entertainment activity for the overall development of the area.

Water wheels have traditionally been used in the Himalayan regions for rice hulling, milling of grain and other mechanical applications. With the R&D efforts, new and improved designs of water mills have been developed for mechanical as well as electricity generation of 3 to 5 kW. These designs were tested at AHEC, IIT Roorkee and have been replicated by about 12 very small scale manufacturers. Local organisations such as the Water Mill Associations, cooperative societies, registered NGOs, local bodies, and State Nodal Agencies are being encouraged to install watermills in their areas. The state of Uttarakhand has taken a lead in setting up electricity generation watermills and over 500 such watermills were installed in remote and isolated areas of the state.

## 12.6 Equipment manufacturing status

India has a wide base of manufacturers of equipment for hydropower projects. State-of-the-art equipments are available indigenously. Fifteen manufacturers produce almost the entire range and type of hydropower equipment. Most of the world's leading equipment manufacturers have their factory and/or offices in India. In addition, there are about 5 manufactures that are producing micro hydro and watermill equipment.

## 12.7 Performance testing of SHP stations

In the hydropower the energy transformation process is highly efficient, usually with well over 90 per cent mechanical efficiency in turbines and about 98 per cent in the generator. The inefficiency is due to hydraulic loss in the water circuit (intake, turbine, tailrace), mechanical loss in the turbogenerator group and electrical loss in the generator. Old turbines can have lower efficiency, and it can also be reduced due to wear and abrasion caused by sediments in the water. The rest of the potential energy (100 per cent – η) is lost as heat in the water and in the generator. Thus energy efficiency measurement is one of the key issues.

The efficiency in electromechanical equipment, especially in turbines, can be improved by better design and also by selecting a turbine type with an efficiency profile that is best adapted to the duration curve of the inflow.
As per MNRE directive the small hydro project when commissioned is required to be tested for its performance by Alternate Hydro Energy Centre (AHEC), Indian Institute of Technology (IIT) Roorkee.

The subsidy is released after project attaining the following:

1. Overall performance of the station should be satisfactory.
2. Plant equipment should conform to Indian/International standards.
3. Weighted average efficiency of generating units should, with certain exceptions, be at least 75 per cent.
4. Project should have attained 80 per cent of projected generation for a minimum of 3 months at a stretch.

The biggest challenge for the performance testing was observed the absence of availability of provisions required for such tests in majority of the commissioned SHP plants. With such initiative SHP developers have started taken keen interest by way providing the necessary provisions in the civil structure/equipment for facilitating the testing. Needless to say that such evaluation shall help SHP plant owners regular monitoring of performance of their plants.

However there is no mandatory condition for performance testing for large hydropower projects until the owner wishes to do so as per contractual conditions. Electricity regulators and financial institutions are being followed up to adopt conditions for remunerative tariff from hydropower.

## 12.8 Benefits of hydropower and reasons for its slow development

Hydropower has immense benefits and has been brought forward as a preferred option for power generation over the last decade. The reasons for these can be summed as follows:

1. Abundant potential of hydropower development in India as discussed above.
2. With relative independence from international market like oil prices, hydropower involves no extra foreign exchange outgo.
3. Hydropower is a no-inflation power as water—the ‘raw material’ for power generation is free of inflation.

4. Environment friendly.
5. Hydropower projects support socio-economic development of remote areas as the project site is developed.
6. Hydropower is cost effective and renewable form of energy.
7. It has additional benefits like irrigation, flood control, tourism, etc.

Even with these benefits, hydropower has had slow development in India especially in last few decades. This has primarily been due to:

1. Long gestation period.
2. Time consuming process for project clearances.
3. Until recently, the national focus has been on thermal generation.
4. Highly capital intensive and absence of committed funds.
5. Poor financial health of State Electricity Boards (SEBs).
6. Technical constraints due to complex geological nature of the projects.
7. Interstate disputes as water is a state subject.
8. Absence of long tenure loans makes it difficult for private investors.
9. Advance against depreciation is disallowed.
10. 14 per cent return on equity (ROE) is not attractive enough for investors.
11. Dearth of competent contracting agencies to construct the project site.

The national focus on thermal generation has been shifting towards hydropower development. To this effect, Government of India introduced a national policy on hydropower development in 1998, in which hydropower has been accepted a national priority with emphasis on unharnessed potential especially in the NE region. Key policy initiatives to accelerate hydropower have been introduced in the policy document, which are discussed in detail in the following section.

## 12.9 National policy on hydropower in India

With the aim to accelerate the development of hydropower, the Ministry of Power (MOP), Government of India (GOI) introduced the National Policy on Hydropower Development in 2004. The policy document has identified and responded to the major issues and barriers. The objectives of the National Policy document on hydropower development, 2004 are (as stated in the chapter):

1. To ensure targeted capacity addition during 9th plan (and the subsequent plans).

2. With Central, State and Private hydropower projects contributing 3455, 5810 and 550 MW respectively, the GOI aims to reach the total capacity of 9815 MW during the ninth plan. (The XIth plan aims capacity addition of 18781 MW in the hydropower sector.)
3. Exploitation of vast hydro electric potential at faster pace.
4. The government would take steps like execution of all CEA cleared projects, update and clear pending DPRs, survey new green field sites and resolve interstate disputes.
5. Promotion of small and mini hydro projects.
6. Small and mini hydro projects are especially viable for remote and hilly areas where extension of grid system is comparatively uneconomical.
7. Strengthening the role of PSUs and SEBs in taking up new hydro projects.
8. The government aims at enlarging Public sector's involvement in mega hydro projects and multipurpose projects involving interstate issues, projects for peaking power and those with rehabilitation and resettlement issues.
9. Increasing private investments for development of hydropower in India.
10. The public sector would be supported by greater private investment through IPPs and joint ventures. Private sector participation is considered vital for large scale development of hydropower.

Through these measures, GOI aims to realise 100 per cent hydropower potential of the country by year 2025–26. These objectives have been developed in response to the following constraints:

1. Technical, including difficult investigation, inadequacies in tunnelling methods.
2. Financial (deficiencies in providing long-term finance).
3. Tariff related issues.
4. Managerial weakness (poor contract management).
5. Geological surprises (especially in the Himalayan region where underground tunnelling is required).
6. Inaccessibility of the area.
7. Problems due to delay in land acquisition and resettlement of project affected families.
8. Law and order problem in militant infested areas.

## 12.10 Development since national hydropower policy 2004

In 2006, Central Electricity Authority (CEA) introduced a ranking study which prioritised and ranked the future executable projects. As per the study, 399 hydro schemes with an aggregate installed capacity of 10,6910 MW were ranked in A, B and C categories depending upon their interse attractiveness. This was followed by a 50,000 MW Hydro Initiative in which preparation of pre-feasibility reports of 162 projects was taken up by CEA through various agencies. The project-feasibility reports (PFRs) for all these projects have been prepared and projects with first year tariff less than INR 2.50/kWh have been identified for preparation of detailed project report (DPR).

### 12.10.1 Renovation, modernisation and up-rating

In order to augment the hydro generation and improve the availability of existing hydropower projects, Government of India has put emphasis on renovation, modernisation and up-rating (RM&U) of various existing hydro electric (HE) power projects in the country. RM&U of the existing/old hydro electric power projects is considered the best option, as this is cost effective and quicker to achieve than setting up of green field power projects. The cost per MW of a new HE power project works out to about INR 4 to 5 crores whereas the cost per MW of capacity addition through up-rating and life extension of old HE power project works out to about 20 per cent. Further, the RM&U of a hydro project can be completed in 1 to 3 years depending upon scope of works as compared to gestation period of 5 to 6 years for new hydro projects.

Under the hydro RM&U program, 33 hydro electric projects (13 up to the VIIIth plan and 20 in the IXth plan) with an installed capacity of 6174.10 MW have been completed by the end of the IXth plan. During the Xth plan (2002–07), 47 HE power projects with an installed capacity of 7449.20 MW are programmed for completion of RM&U works. For the XIth plan (2007–12) a total of 59 hydro electric power projects having an installed capacity of 10325.40 MW are programmed for completion of RM&U works to accrue a benefit of 5461.18 MW.

### 12.10.2 Capacity addition scenario XIth plan (2007–12)

In support to the 2004 national hydropower policy, GOI plans to wipe out all energy shortage by the end of 2011–12, i.e. by end of XIth Plan and also to provide spinning reserve and ensure uninterrupted quality power at affordable cost. With coal based power plant as the backbone of Indian Power sector, during the XIth plan capacity addition of about 40200 MW coal based plant is planned with introduction of supercritical technology (Table 12.2).

**Table 12.2** Sector-wise plan of capacity addition in XIth plan.

| Prime mover | Hydro (MW) | Thermal (MW) | Nuclear (MW) | Total (MW) |
|---|---|---|---|---|
| State sector | 3957 | 15,538 | – | 19,495 |
| Central sector | 11,080 | 19,880 | 3160 | 34,120 |
| Private sector | 3744 | 11,145 | – | 14,889 |
| Total | 18,781 | 46,563 | 3160 | 68,504 |

### 12.10.3 Three-stage clearance system

A three-stage clearance system has been set up to enable relatively faster and hindrance free clearance of suitable projects and includes survey, investigation and pre-construction activities. The three-stage clearance system works as under:

Stage I: Survey and preparation of pre-feasibility reports.

Stage II: Detailed investigation, preparation of DPR and pre-construction activity including land acquisition.

Stage III: Execution of the project after investment decision through PIB/CCEA.

Small hydropower projects up to 25 MW can be set up in private sector without Central government's involvement. Techno-economic clearance needs to be obtained from CEA if the estimated cost of the project exceeds INR 2500 million and/or there are interstate issues involved.

## 12.11 Current issues/problems with hydropower in India

The Government of India set up a National Committee in 1987 and a Standing Committee in 1998 to oversee the progress on hydropower development.

This section derives largely from the report submitted by the Standing Committee on Energy (2005–2006)—Hydropower: a Critique which discusses the actions taken by the Government on the recommendations made by the Committee in the forty-second report on hydropower in India.

### 12.11.1 Technical issues

1. To expedite early execution of hydro projects, bankable detailed project report (DPR) based on detailed survey should be prepared to avoid geological uncertainties. Survey and investigation and analysis of geological, geo-morphological, geo-electrical, hydrological data, etc. should be done at the time of preparation of a DPR itself in order to minimise the impact of risks. It is, therefore, necessary to expedite survey and investigations with the latest state of the art technology and prepare a shelf of projects for execution. The quality of DPRs should be of high standard which should infuse confidence in the national/international developers to take up the execution of projects without losing time in rechecks, etc. at the same time, contract monitoring as distinct from project monitoring should be emphasised and land acquisition and infrastructure development be settled and completed before the start of the project.
2. Renovation and modernisation (R&M) has been recognised world over as a well proven cost effective technique for improving the performance/efficiency of older power plants. The useful life of the plants can be increased by R&M and the plants yield benefits in the shortest possible time at a reasonable cost. GOI in its policy on hydropower development, 1998 has laid stress on need for renovation and modernisation of hydropower plants. Accordingly, Government of India set up a Standing Committee to identify new hydro R&M schemes to be undertaken for implementation under Phase-II.
3. The pump storage potential should be harnessed as these are essential in optimising energy generation from base load thermal stations and in meeting peak load and system contingencies. Only 2.45 per cent of total identified potential of 94,000 MW pump storage schemes had been harnessed and another 2.5 per cent are under construction. New exclusive program/action plan for PSS should be launched, to tap the vast potential.
4. Contingency plan for hydro projects affected by natural calamities need to be prepared and made public.
5. National policy on rehabilitation and resettlement (R&R) should be finalised and made public.

### 12.11.2 Infrastructural issues

1. There is a need to setup single window clearance for hydro projects. Various authorities such as the Central Electricity Authority (CEA), the Ministry of Finance, Ministry of Environment and Forests, etc.

are involved in the appraisal of a hydropower project before it is certified for development. It will be desirable to have a single window dispensation/authority so that a project is cleared without many hassles. Any hydro project submitted for clearance should receive all the statutory/non-statutory clearances/approvals within six months of submission of the proposal. The certification of commercial viability should be given within 15 days, especially to private developers. The techno-economic, MoEF and CCEA clearances should be given within 1 and 2 months respectively. The Ministry of Power should have a set of hydro projects cleared from all the angles. MoEF should also be involved in the appraisal process.

2. There are long delays on account of land acquisition for the project. The process of land (both private and Govt.) acquisition for a project differed from state to state as per Land Acquisition Act. The Government should amend Land Acquisition Act and include hydropower projects in the priority list and the State Governments should be persuaded to provide land to the project authority in agreed time frame to facilitate shifting of project affected persons (PAPs).
3. The hydro projects which involve lesser risk element and entail lesser capital investment can be considered for development in the private sector. Public sector can take up: (i) multipurpose projects, (ii) projects involving interstate issues and in interstate river systems, (iii) projects involving cooperation with neighbouring countries, (iv) projects for complementary peaking with regional benefits, and (v) projects in the North–Eastern region, etc.

### 12.11.3 Financial issues

There is also a need to off-load indirect cost components on hydro project. Many hydro projects are located in troubled areas and infested by militancy and terrorist activities. There is an urgent need to amend the present policy of the Government in regard to charging the entire security expenditure from concept and until commissioning—on the project cost. However, the recurring expenditure incurred on security, once a project goes on stream could to be charged on the project developer.

The cost of access roads should not be included in the project cost, as development of hydro projects triggers economic and commercial activities around the project site and results in economic benefit to the state. Inclusion of R&R, flood moderation costs, along with the provision of 12 per cent free power to the state in the capital cost of the project needed reconsideration as the provision did not apply to thermal power projects.

Although the government has planned to achieve 50,000 MW of additional power by the end of 11th plan period, the incentives such as benefits/ concession in custom duties and local levies/taxes on project components are being denied for projects even up to 250 MW resulting in low investments in new power schemes.

A premium as well as lease rent @10 per cent is charged where forest land is diverted for a hydropower project. This needs to be discussed with the state governments as land is a subject matter.

## 12.12 State-specific hydropower issues

### 12.12.1 Issues related to hydropower development in Uttarakhand

Uttaranchal has an estimated hydropower potential of 20,236 MW against which only about 1407 MW has been harnessed so far. The Government of Uttarakhand (GOU) has introduced separate policy guidelines for development of hydropower projects of capacity up to 25 MW and 25–100 MW. The policy promotes small hydropower (SHP) projects with installed capacity of up to 25 MW through IPP. The main issues from the policy document are discussed as follows.12.12

#### *Lack of detailed project reports (DPRs) and technical data*

Lack of bankable DPRs of the projects for development in the private sector before their allotment makes it very difficult for the private investors/developers to take investment decisions. Similarly technical data on availability of water at the diversion site of the project should be made available to the developer before project allocation. Currently, river discharge observations are not made available to the developers on pretext of confidentiality and are made available to the concerned government department only after the approval of the Ministry of Water Resources, GOI. Considerable time is lost in getting the approval. It is suggested that the states should organise measurement of hydrological and meteorological data of all identified sites of hydroelectric projects through Central Water Commission or other dependable agencies. The data collected should be made available to the developers allowing for better assessment of river hydrology and reduced hydrological risk.

#### *Project allotment on the basis of premium*

Allotment for projects above 100 MW is made on the basis of the highest bid received from the developers after short listing. The premium paid by the developers increases the tariff, making hydropower expensive. It is suggested that the promoters should be selected on the basis of their competence and experience and not alone on the basis of premium.

### *Upfront fee*

The developers are charged an upfront fee of INR 5 lacs per MW by the state. This increases the cost of electricity generated by hydropower making implementation of Electricity Act 2003 difficult.

### *Land procurement and development cost*

The policy on land provision for hydropower differs from state to state. While in Uttarakhand the land is available at market price for project development, Uttar Pradesh government provides land at INR 100 per acre. This difference in land cost makes hydropower development very difficult in few states as compared to others. It is suggested that the land for project development should be acquired by the state and handed over to the project developer.

The state should provide for the cost of approach roads, resettlement and rehabilitation of the project affected people instead of loading the cost on the project.

### *Payment security*

The states with hydro potential are generally power surplus making hydropower power sale financially less lucrative. It is suggested that the State should guarantee to buy power from developers at the rates fixed by the Regulatory Commission. They should also be allowed to sell the power independently, if so desired by them.

### *Back loading the free power*

Being capital intensive, the tariff in hydroelectric projects is high during initial years of project operation. If free power is back loaded, the tariff during the initial years will be reduced, thus making hydropower more competitive compared to other sources of power.

## 12.12.2 Issues related to hydropower development in Himachal Pradesh

The total identified potential in HP is 20386.07 MW. Out of this 6045.07 MW has been harnessed so far and 2720.5 MW is under execution. For which DPR is ready for 3011.50 MW, projects for 3671.50 MW are Under Investigation and 4187.50 MW of schemes are yet to be investigated. The main issues related to Hydropower development in the state are as follows.

#### *Purchase rate of power by state*

In Himachal Pradesh the purchase rate of power was fixed as INR 2.50 in 1997–98 for small hydro. Since then, the cost of steel, cement and labour has increased considerably. However, the purchase rate for hydropower has not been revised by the state. It should be revised at the earliest.

#### *Local area development*

In HP 1.5 per cent of the project cost is realised from the developers for local area development. This unnecessarily increases the tariff. As stated above, the local area development should be paid from the revenue of free power received by the State.

#### *Fishery department compensation*

Compensation at the rate of INR 5 lac per MW and 1 lac per km of breeding area lost due to project is payable by the developer. It is suggested that the developer should not be made liable for this.

#### *Charges for augmentation of transmission system of HPSEB*

It is understood that Himachal Pradesh State Electricity Board is going to charge INR 40 lac per MW from developers for augmentation of transmission system beyond interconnection point. This should be reconsidered.

### 12.12.3 Recommendations for hydropower development in Himachal Pradesh

Various issues and barriers to large scale development have been identified in the above discussion. As the first step towards hydropower development, the state government guarantee has been withdrawn comforting financers as well as Independent Power Producers (IPPs). Following policy recommendations are suggested to the Government of Himachal Pradesh to further attract significant investment in the sector of Hydropower.

#### *One-stop window for clearances*

Private investors expect clear rules, a streamlined application process and a reasonable timeline for response from the HP state government.

Several clearances including IPH, Public Water Department (PWD), Gram Panchayat, Wildlife, Forest, conversion of private land under section 118 of HP. Land Reforms and Tenancy Act, No-objection certificate (NOC) from Fisheries Dept. and NOC from Pollution Control Board are to be taken within the six months time. The offices of respective departments are located in different places and the given time frame is very inadequate for the application process.

The procedure should be simplified. Once the project is conceived, the government should indirectly give clearances to set it up. Considering the small size of projects, the government should give one clearance to cover all the items. Alternatively, there should be a single point body to give the clearances.

### *Streamlining fees and royalties*

Several added costs have burdened the project. The net present value (NPV) payment for government land to Forest Dept., fees to Pollution Control Board and compensation to Fisheries Dept. are significantly high. Recently, new norms for Fisheries have been proposed @INR 5 lacs per MW and INR 1 lac per kilometre (KM) upstream of tail race which may add up to 30 lacs for a 5 MW project.

In addition, government is proposing a development fund of 1 to 1.5 per cent of the project cost for local development works which can be up to INR 40 lacs for a 5 MW project. The NPV compensation to Forest Department also can be up to INR 40 to 50 lacs for the project land and transmission line. All these total to more than INR 100 lacs per project.

Recent news in the press suggest that 15 per cent water is to be released for downstream use. Earlier a provision of 10 per cent was made. During lean season, the plant may have to be shut down. The wheeling charges and transmission charges should be fixed for projects up to 25 MW. Currently, there is no such provision and it is to be decided by the ERC. There should be a government policy.

The IA draft has been revised in the recent past. There are some provisions which should be reviewed, e.g. Arbitration by sole Arbitrator and he is Secretary to Government of Himachal Pradesh (GOHP) other than Energy Secretary. There is a penalty or extension fee of INR 10,000 per month per MW proposed for extension beyond 6 months. Only one extension of 6 months is allowed. This time frame is inadequate. The IPP is anyway incurring cost on the project and should not be burdened with such extra fees.

### *Escalation inclusive tariff*

A tariff of INR 2.50 per unit for 40 years is unrealistic. The prices of cement and steel have significantly increased, and an escalation provision must be added.

### *Transparency in land acquisition*

The private land owners have started asking very high price from IPPs. The government should acquire land for the project and provide to IPPs at a fair cost.

### *Expansion of transmission*

The transmission system as existing is inadequate to cater to large number of small projects which will need to be developed in HP. Evacuation is required at a manned substation. Substations are also limited and located very far from the projects requiring longer transmission lines. Besides high cost towards forest compensation and long transmission lines, there are transmission losses. HPSEB is implementing a master plan with multilateral funds, e.g. Asian Development Bank, etc. for improving the infrastructure in transmission. This revamping should be done keeping the requirement of small projects in view. HPSEB is undertaking a policy that IPPs shoulder the expenditure towards improving the basic transmission infrastructure beyond interconnection point. This should not be burdened on the projects.

Several projects have been awarded in different regions with limited availability of substations for interconnection. A few substations have already started facing a space and capacity crunch. As a result, the evacuation is becoming difficult as well as expensive because the capacity is sent to other substations located at longer distances.

## 12.13 Establishment of R&D hydraulic turbine laboratory

An R&D hydro turbine laboratory of international level being established at AHEC IIT Roorkee with the financial support from MNRE, at AHEC, IIT Roorkee for the multiple purposes, viz. turbine-model testing, research and development (R&D), human resource development (HRD) along with the other purposes of verification of designs, generation of design data, design validation through CFD analysis, witnessing tests on turbines/pumps in field. The laboratory is expected to be fully functional by the end of year 2012.

## 12.14 Standards for small hydropower

There is a series of standards, guidelines and manuals on hydropower issued by international standards organisations like ISO, IEC, IEEE, ASME, USBR and the national statuary bodies of several countries, including India where it has from CEA, REC, BIS and CBIP. But most of them were prepared keeping in view the large water/hydropower projects. SHP needs to be made profitable and a long-term investment opportunity, while ensuring quality and reliability of the power. To make SHP cost effective and reliable, standards, guidelines and manuals are required covering entire range of SHP activities. Necessity of the standards/guidelines and manuals has been strongly felt by developers, manufactures, consultants, regulators and others. The efforts of Government of India have taken initiatives to prepare about 30 standards for SHP and are expected available by the year 2013.

## 12.15 Real time simulator

Training and human resource development is given due importance by the ministry of new and renewable energy. Towards this, apart from regular training programs, a real time digital simulator (RTDS) for SHP plants has been established at alternate hydro energy centre (AHEC), IIT Roorkee, and India with the aim of providing efficient initial and advanced training to operators and engineering staff of different types of SHP plants.

Training conditions have been created very close to real operating conditions. This will meet the large requirement of trained personnel for operation and maintenance of SHP plants, reduce O&M costs, reduce damage to plant, increase plant life and reduce training time. The hydraulic part, the generator, the transformers as well as auxiliary electricity systems are taken care in the simulation. Present and future operators are taking the benefits of such training and is being utilised by national and international personnel.

## 12.16 Performance of Tawa hydroelectric power plant

Small hydropower project may be used as one of the option for achieving the energy targets in a developing country like India where centre or state governments have limited financial resources to put in large projects which require long gestation period. One additional advantage with the small hydropower project is that private partners may get attracted due to low investment and quicker return in comparison to large projects. The last but not least is the most ecofriendliness of small power projects which is a point of serious concern in case of thermal, or nuclear or sometimes in big Hydropower projects depending upon the location of the projects.

Small hydropower potential in India is still underutilised and there is need to tap this potential for optimum utilisation of natural resources. In Madhya Pradesh, small hydro plants are not many; however there is good scope for developing such plants. Tawa is one of such plants in MP, which has been developed as canal head powerhouse on the left bank canal (LBC) of Tawa irrigation project by a private investor. This plant is working in a very efficient manner addressing both the power and irrigation aspects successfully. This example will attract the private investments in small hydropower sector in the developing countries like India.

Hydropower is a renewable, non-polluting and environment friendly source of energy. It is perhaps the oldest energy technique known to mankind for conversion of mechanical energy into electrical energy. Hydropower represents use of water resources towards inflation free energy due to absence of fuel cost. Hydropower contributes around 22 per cent of the world electricity supply generated. The total potential of small hydropower of the whole world is 7,80,000 MW out of which 50,000 MW has already been utilised.

Small hydro is also the highest density resources in generation of electricity due to the reason of being it environment friendly, flexibility in operation and suitability in giving support in peak time to the local grid.

Due to the small gestation period, small capital investment and quicker return involved, in recent years it has become the point of attraction for private sector. Fiscal incentive announced by the central and state governments time to time for investment in this sector have further caused private investor to give attention to this sector.

Small hydropower plants (SHP) provide maximum benefits in minimum time. And offers the fastest economical means to enhance power supply, improve living standards, stimulate industrial growth and enhance agriculture with the least environmental impact and without heavy transmission losses. Due to less transmission losses there is a reduction in distribution cost as well. Its availability at the head of the irrigation canals and small streams is also a one of the added advantage of it.

## 12.17 Small hydro development in India

India has a rich history of small hydropower development. The first hydropower plant was set up in the year 1897 with a capacity of 130 kW in Darjeeling district. After independence due to increase in power requirement the thrust shifted from small hydropower to large size hydro and thermal project.

After opening of our economy and envisaging an aspire growth rate of 7–8 per cent, the need of energy at low cost has been felt much. Here it would be desirable to clarify that India is a developing country, which cannot afford to invest huge amount of money in only large projects with long gestation period, and hence it was felt more reasonable also to go for small hydropower project with participation of private sector. Further the small gestation period and its ability to cater local grid need, with minimum transmission losses reinforced the idea for going towards small hydropower projects. It was felt by the ministry of power that out of total power of the grid to be installed, 2 per cent should come from small hydropower and if this is translated into reality then by 2013 there will be an addition of 2000 MW capacity from small hydropower.

India has a potential of 15000 MW. To tap this potential 4404 potential sites with an aggregate capacity of 10477 MW have already been identified. The installed capacity of SHP project as on 31.03.2008 is 1826 MW from 556 projects. In addition 203 SHP projects with an aggregate capacity of 468 MW are under completion. The growth of capacity addition from small hydro projects during last few years is on an average 100 MW per year.

### 12.17.1 Scope for investments in small hydropower sector

There is lot of scope for investment in small hydropower sector. Very few power plants are under the private sector management. One of such hydroelectric plant, which is working successfully, is Tawa hydroelectric power plant under the efficient management of M/s HEG (Hindustan Electro Graphite Ltd.) in Madhya Pradesh (MP).

Hydroelectric power is one of the cleanest and most viable renewable sources of energy. Government has been constantly promoting setting up of non-conventional power plants, including hydro, through various policies, incentives and agencies specially created for this purpose. The policies formulated so far by the central and state governments had been all encompassing and applicable to all kinds of non-conventional power producing sources like, wind, biomass, solar, municipal solid waste and hydro.

### 12.17.2 Status of private participation in India in small hydropower sector

After adaptation of liberalisation policy in year 1991 it was felt necessary to open the energy sector to private partners. In order to achieve the targets set up by Government of India to cater the requirement of power in coming years state as well as central nodal agencies were set up to provide assistance for obtaining necessary clearance in allotment of land and project site to private partners. A provision was also set in the electricity act of 2003 to set up state electricity Regulatory commissions, which would promote generation of electricity from non-conventional sources by providing suitable measures for connectivity with grid. In continuation of this till now 16 states have policies (including Madhya Pradesh) for private sector participation. These states have offered sites to private sector to achieve an aggregate potential of 2500 MW. So far over 120 SHP projects with a total capacity of 500 MW have been set up in private sector in Andhra Pradesh, Karnataka, HP, Punjab, Uttarakhand and Maharashtra.

Ministry of non-conventional energy sources has been providing subsidiary for public sector as well as private sector. In case of private sector, subsidiary is released after successful commissioning of the project. Renewable Energy Development Agency (IREDA) and Rural Electrification Corporation are providing loan assistance for setting up of small hydropower projects. The financial assistance is also being provided by World Bank through IREDA.

### 12.17.3 Status of small hydropower sector in Madhya Pradesh

The estimated potential for generation from small hydropower projects (SHPs) is 15,000 MW in India, out of which in undivided MP, estimated potential is 410 MW. Despite various promotional schemes and measures announced by MP government, it could set up only 41 MW of SHPs which is only 2.2 per cent of national installed capacity of 1826 MW, as GOI aims to provide 10 per cent of gross power generation in the country through non-conventional energy sources by the year 2013. Therefore MP state has to travel very long distance and sincere efforts needs to be made, especially to make up the deficit in the small hydropower sector.

### 12.17.4 Policy on SHP in Madhya Pradesh

MP sate government like other state governments and central government had announced policy on small hydropower and on the participation of private sector to increase the small hydropower generation in the state. The main objectives of the policy are:

1. To promote generation of power through small hydropower projects with private sector participation.
2. To define the incentives and benefits available to a private sector.
3. To create a favourable environment for promoting the sector.
4. To lay down the framework for the implementation of the project.

## 12.18 Case study: Power plant in private sector in Madhya Pradesh

Tawa project is an irrigation project located on River Tawa a tributary of Narmada river. The river Tawa, which is one of major tributaries of River

Narmada, rises from the Satpura range of hills at an elevation of 2500 ft (762.00 m).

The head works comprises earthen dam of average height 22.528 m and masonry dam of 57.912 m heights with central masonry spillway. 13 no. radial gates each of size 15.24 m × 12.192 m are provided with spillway crest at a RL 343.205. The MWL of the dam is 356.692 m. The right bank canal has a cultural command area of 98079 ha and an annual irrigation of 75878 ha (Kharif, Rabi and Summer crops). The left bank irrigation canal has cultural command area 1,86,162 ha and an annual irrigation area of 2,56,904 ha (Kharif, Rabi, and Summer crops).

### 12.18.1 Hydroelectric plant

Small hydropower plant was setup on left bank to utilise the tailrace water for irrigation purpose. The tailrace channel from the powerhouse leads to LBC. The two units of 2 × 6.75 MW were setup by M/s HEG Ltd., Mandideep. The Power production in this plant was started in the year 1998. During Kharif and Rabi season the water is supplied through powerhouse tailrace channel to command area for irrigation.

### 12.18.2 Highlights of project

1. The construction of the project was completed in record time of 22 months and at a cost of around 65 crore against the estimated time of 40 months and Rs. 75 crore estimated cost.
2. Early and efficient completion made possible by RSWI, Canada (Joint Venture Company of India and Canada).
3. Optimal scheduling and project monitoring.
4. Low on capital cost and efficient in generation.

### 12.18.3 Technical highlights

1. Canal head project
2. Catchments area spreads over approximately 6000 sq. km
3. Full reservoir level (FRL) 335.397 m
4. Head range 7 to 21 m and discharge varying from 25 to 54 cumecs
5. Two turbo generators 6.75 MW rated capacity (20 per cent overload)

### 12.18.4 Machinery and equipment

1. Vertical shaft kaplan turbines and its auxiliaries

2. 11 kV semi umbrella synchronous generator ad auxiliaries
3. 33 kV vacuum circuit breakers
4. 1 MW 33 kV/415 V auxiliary transformer.
5. Fire protection system
6. 110 DC with battery back up

### 12.18.5 Performance of Tawa Hydroelectric Plant (Year 2006–07)

The generation of hydropower depends mainly on storage of dam resulting due to rainfall. The southwest monsoon arrives in Madhya Pradesh state around June 15th and withdraws by October 15. The reservoir filled up to and above FRL during the past five years.

It is a known fact that small hydropower offers maximum benefit with least environmental impact and less investment compared to other conventional source of energy. On the basis of the following data and discussion it has been tried to establish that small hydropower plays an important role in development of the country with minimum maintenance cost as far as non-conventional energy sources are concerned.

The study of the available data indicates that the plant was neither shut down nor there was any major break down observed during the period 2006–07. This also shows the efficient management, technical expertise and well maintained condition of the plant by the company with optimum technical manpower. It is also learnt that plant worked in the same efficient manner since the year when power generation was started in 1998.

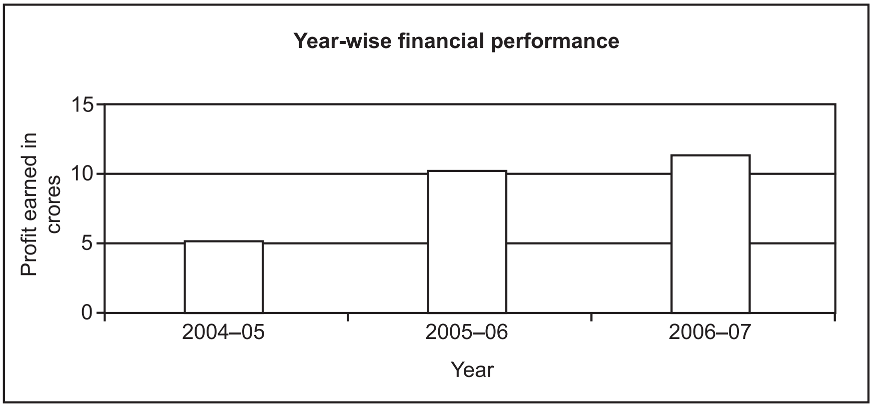
Performance details of plant

| | |
|---|---|
| Period of generation | 4200 hrs |
| Duration of power generation in % | 48% |
| Power production | 5.720 crore units |
| Performance | 94% |
| Technical manpower deployed | Two technicians per shift |
| | One engineer per shift |
| | (8–10 technicians per day) |
| Highest post at plant | One GM |
| Total manpower | 26* |

| Year | Reservoir water level on Oct. 15th in m | FRL in m | Generated units (crores) | Approximate selling rate (Rs.) | Approximate revenue in crores of Rs. | Benefit in crores of Rs. |
|---|---|---|---|---|---|---|
| 2004–05 | 354.086 | 335.397 | 3.00 | 2.30 | 6.9 | 5.4 |
| 2005–06 | 355.397 | 355.397 | 5.20 | 2.30 | 11.96 | 10.46 |
| 2006–07 | 355.427 | 355.397 | 5.70 | 2.30 | 13.11 | 11.61 |

Approximate expenditures details in plant maintenance for one year.

| S. no. | Description | No. | Days/ Month | Rate (Rs.) | Month/ Day | Amount (Rs.) |
|---|---|---|---|---|---|---|
| 1. | Water charges | | | | | |
| | The water charges are to be paid at the rate of Rs. 60,000/day if the unit runs completely, since there was no breakdown /shut down | – | 175 | 60,000 | Day | 1,05,00,000 say 1 crore |
| 2. | Establishment charges | | | | | |
| | General manager | 1 | 12 | 40,000* | Month | 4,80,000 |
| | Engineer | 3 | 12 | 20,000* | Month | 7,20,000 |
| | Technicians | 10 | 12 | 10,000 | Month | 12,00,000 |
| | Other staff | 12* | 12 | 7000* | Month | 10,08,000 |
| 3. | Annual maintenance charges | – | – | – | LS | 10,00,000* |
| | *Approximate charges | | | | Total Rs. | 1.49 crores |




Thus, in order to achieve a growth rate of 7–8 per cent as envisaged in National policy of India, it is also required to tap all the small hydropower potential of the country. The encouraging performance shown by the Tawa project itself set an example for inviting private investment in the small hydropower project sector, especially in view of the fact that large hydropower projects involve huge capital investment and long gestation period which private partners do not afford to bear. The utilisation of small hydropower potential is especially required in all states where the utilised potential is very low like in MP and therefore optimum utilisation of the same may set up a stepping up stone for achieving self-sufficiency in power sector in country.

## 12.19 Way ahead

Government of India is vigorously promoting large scale development of hydropower in India through changes in policies, all driven to involve greater private entrepreneurs. The major issues plaguing the hydropower sector have been identified and policy changes to mend these barriers are now required. These issues have been discussed earlier in the chapter.

The way ahead to meet the energy demand is as follows:

1. The recommendations made by the Standing Committee for hydropower development are crucial and should be enforced for maximum benefit to the Indian hydropower sector.
2. Consistent policies and regulations should be made through the states. Any variation in policies and benefits offered by different states will cause problems in development of many project sites in different states.
3. Large scale hydro projects which involve greater risks due to geological uncertainties, etc. should be implemented by the state nodal agencies, while the relatively safer projects with reduced risks and smaller capital investments should be offered to the private entrepreneurs.
4. A single window clearance setup for hydro projects will solve most problems related to the clearances, etc.
5. Renovation and modernisation of existing/old hydropower plants should be promoted and planned for, instead of complete focus on setting up of green field power projects.
6. Financial issue like long-term debt financing/long tenure loans, differential tariff for peak and off-peak hours need serious thinking and early implementation.
7. The private sector participation in the large scale development of hydropower should be promoted. This can be achieved either through public–private partnerships or through independent private projects (IPP way). The Government of India has already recognised the need

to increased private involvement and has referred to it in the national policy document.

8. The hydro sector needs to develop a set of competent civil engineers/ contracting agencies that have the technical and the management expertise to conceptualise and develop a project of the required scale. The contract management practices with a transparent system of selection of contractors and resolve any disputes that may arise need to be reviewed
   (a) Underground works (like tunnel, powerhouse, surge tanks)
   (b) Pooling of electricity and marketing
   (c) Efficient operation of hydro reservoirs
   (d) Hydrological estimation planning
   (e) Overall planning and design consultancy

# 13
# Tide, wave and ocean energy

## 13.1 Introduction

Tidal power, also called tidal energy, is a form of hydropower that converts the energy of tides into useful forms of power—mainly electricity. Although not yet widely used, tidal power has potential for future electricity generation. Tides are more predictable than wind energy and solar power. Among sources of renewable energy, tidal power has traditionally suffered from relatively high cost and limited availability of sites with sufficiently high tidal ranges or flow velocities, thus constricting its total availability. However, many recent technological developments and improvements, both in design (e.g. dynamic tidal power, tidal lagoons) and turbine technology (e.g. new axial turbines, crossflow turbines), indicate that the total availability of tidal power may be much higher than previously assumed, and that economic and environmental costs may be brought down to competitive levels.

## 13.2 Tides

There are two high tides and two low tides around the earth at any instant. One high tide is on the longitude closest to the Moon and the other on the longitude furthest from the moon. The low tides are on the longitudes at 90° to the longitudes where the high tides are situated. On any given longitude the interval between high tides is approximately 12 hours 25 minutes. The difference in height between a high tide and a low tide is called the tidal range. The mid-ocean tidal range is typically about 0.5–1.0 metres but is somewhat larger on the continental shelves. In the restricted passages between islands and straits the tidal range can be significantly enhanced, up to as much as 12 m in the Bristol Channel (UK) and 13 m in the Bay of Fundy (Nova Scotia). Tidal power has the advantage over other forms of alternative energy of being predictable. For conventional tidal power generation it is necessary to construct huge tidal basins in order to produce useful amounts of electricity. However, in recent years, an alternative technology for exploiting strong tidal currents has been under development using underwater rotors, analogous to wind turbines. Table 13.1 shows the potential of some large tidal range sites in various locations around the world.

### 13.2.1 Physical cause of tides

The main cause of tides is the effect of the moon. The effect of the sun is about half that of the moon but increases or decreases the size of the lunar tide according to the positions of the sun and the moon relative to the earth. The daily rotation of the earth about its own axis only affects the location of the high tides.

**Table 13.1** Tidal potential of some large tidal range sites.

| Country | Site | Mean tidal range (m) | Basin area ($km^2$) | Capacity (GW) |
|---|---|---|---|---|
| Argentina | Golfo Nuevo | 3.7 | 2376 | 6.6 |
| Canada | Cobequid | 12.4 | 240 | 5.3 |
| India | Gulf of Khambat | 7.0 | 1970 | 7.0 |
| Russia | Mezen | 6.7 | 2640 | 15.0 |
| Russia | Penzhinsk | 11.4 | 20,530 | 87.4 |
| UK | Severn | 7 | 520 | 8.6 |

For simplicity we assume that the earth is covered by water. Consider a unit mass of water situated at some point P as shown in Fig. 13.1. The gravitational potential due to the moon is given by:

$$\phi = -\frac{Gm}{s}$$

where, G is the gravitational constant, m is the mass of the moon, and s is the distance from P to the centre of the moon. For d p r we can expand 1/s as follows:

$$\frac{1}{s} = \frac{1}{[d_2 + r_2 - 2dr\cos\theta]^{\frac{1}{2}}} = \frac{1}{2}\left[1 + \left(-\frac{2r}{d}\cos\theta + \frac{r^2}{d^2}\right)\right]^{-\frac{1}{2}}$$

$$= \frac{1}{d}\left[1 + \frac{r}{d}\cos\theta + \frac{r^2}{d^2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + \dots\right].$$

The first term in the expansion does not yield a force and can be ignored. The second term corresponds to a constant force, $Gm/d^2$, directed towards N, which acts on the earth as a whole and is balanced by the centrifugal force due to the rotation of the earth–moon system. The third term describes the variation of the moon's potential around the earth. The surface profile of the water is an equipotential surface due to the combined effects of the moon and the earth. The potential of unit mass of water due to the earth's gravitation is gh, where, h is the height of the water above its equilibrium level and $g = GM/r^2$ is the acceleration due to gravity at the earth's surface, where, M is the mass of the earth. Hence, the height of the tide $h(\theta)$ is given by:

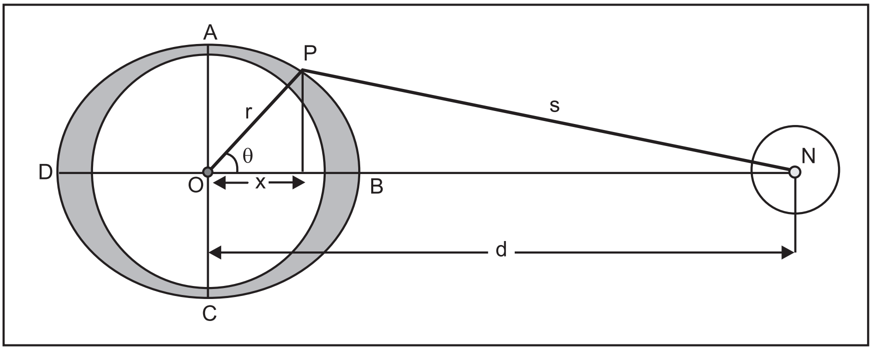



**Figure 13.1** Tidal effects due to the moon (not to scale)

$$gh(\theta) - \frac{Gmr^2}{d^3}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) = 0$$

or

$$h(\theta) = h_{max}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) \qquad \text{... (13.1)}$$

where,

$$h_{max} = \frac{mr^4}{Md^3} \qquad \text{... (13.2)}$$

is the maximum height of the tide, which occurs at points B and D ($\theta = 0$ and $\theta = \pi$). Putting $m/M = 0.0123$, $d = 3{,}84{,}400$ km, and $r = 6378$ km we obtain $h_{max} \approx 0.36$ m, which is roughly in line with the observed mean tidal height.

## 13.2.2 Tidal waves

There are two tidal bulges around the earth at any instant. A formula for the speed of a tidal wave in a sea of uniform depth $h_0$ is obtained from shallow water theory as:

$$c = \sqrt{gh_0}. \qquad \text{... (13.3)}$$

The tidal bulges cannot keep up with the rotation of the earth, so the tides lag behind the position of the moon, the amount dependent on latitude. The presence of continents and bays significantly disturbs the tides and can enhance their range.

### 13.2.3 Shallow water theory

We consider a wave such that the wavelength $\lambda$ is much greater than the mean depth of the sea $h_0$. We also assume that the amplitude of the wave is small compared with the depth, in which case the vertical acceleration is small compared with the acceleration due to gravity, g.

Hence the pressure below the surface is roughly hydrostatic and given by:

$$p = p_0 + \rho g(h - y) \quad \text{... (13.4)}$$

where, $p_0$ is atmospheric pressure and $y = h(x, t)$ is the wave profile on the free surface (Fig. 13.2). Differentiating Eq. 13.4 with respect to x we have $\partial p/\partial x = -\rho g \partial h/\partial x$. Neglecting second-order terms, the equation of motion in the x-direction is of the form:

$$\partial u/\partial t = -g\partial h/\partial x \quad \text{... (13.5)}$$

Since $h(x, t)$ is independent of y it follows from Eq. 13.5 that u is also independent of y. This allows us to derive an equation of mass conservation in terms of u and h. Consider a slice of fluid between the planes x and $x + \delta x$. The volume flowing per second is uh across x and $(u + \delta u)(h + \delta h)$ across $x + \delta x$. By mass conservation, the difference in the volume flowing per second from x to $x + \delta x$ is equal to the volume displaced per second vdx in the vertical direction. Hence:

$$uh = (u + \delta u)(h + \delta h) + v\delta x$$

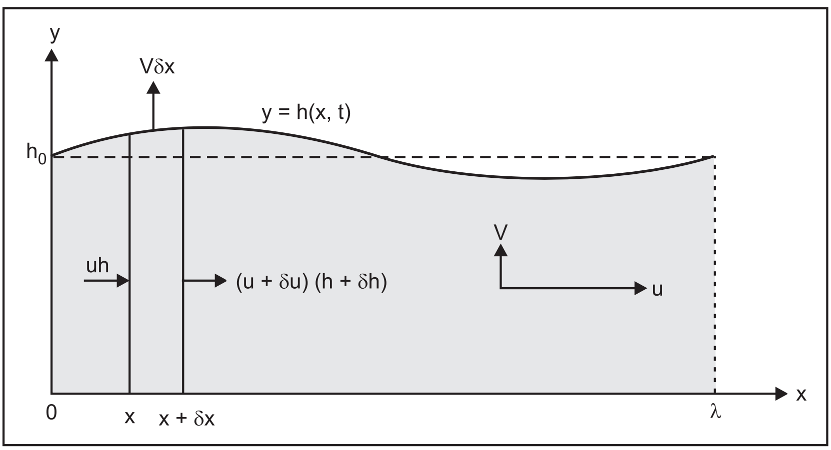



**Figure 13.2** Shallow water wave

Putting $v = \partial h/\partial t$, $\delta u \approx (\partial u/\partial x)\delta x$, $\delta h \approx (\partial h/\partial x)\delta x$, and noting that $h\partial u/\partial x$ p $u\partial h/\partial x$ and $h \approx h_0$, yields the mass continuity equation as:

$$-\frac{\partial u}{\partial x} = \frac{1}{h_0}\frac{\partial h}{\partial t} \quad \text{... (13.6)}$$

Eliminating u between Eqs. 13.5 and 13.6, we obtain the wave equation:

$$\frac{\partial^2 h}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 h}{\partial t^2} \quad \text{... (13.7)}$$

for the height profile h(x, t) of the wave, where $c = \sqrt{gh_0}$ is the wave speed.

## 13.3 Tidal power

The earliest exploitation of tidal power was in tidal mills, created by building a barrage across the mouth of a river estuary. Sea water was trapped in a tidal basin on the rising tide and released at low tide through a waterwheel, providing power to turn a stone mill to grind corn. Tidal barrages for electricity generation use large low-head turbines and can operate for a greater fraction of the day. An important issue is whether it is better to use conventional turbines that are efficient but operate only when the water is flowing in one particular direction or less efficient turbines that can operate in both directions (i.e. for the incoming and the outgoing tides). The first large-scale tidal power plant in the world was built in 1966 at La Rance in France. It generates 240 MW using 24 low-head Kaplan turbines. A number of small tidal power plants have also been built more recently in order to gain operational experience and to investigate the long-term ecological and environmental effects of particular locations. Various proposals during the last century to build a large-scale tidal barrage scheme for the River Severn in the UK have been turned down due to the large cost of construction, public opposition and the availability of cheaper alternatives.

## 13.4 Power from a tidal barrage

A rough estimate of the average power output from a tidal barrage can be obtained from a simple energy balance model by considering the average change of potential energy during the draining process. Consider a tidal basin of area A as shown in Fig. 13.3. The total mass of water in the tidal basin above the low water level is $m = \rho Ah$, where, h is the tidal range. The height of the centre of gravity is ½h, so the work done in raising the water is mg(½h) = $\frac{1}{2}\rho gAh^2$. Hence the average power output is:

$$P_{ave} = \frac{\rho gAh^2}{2T} \quad \text{... (13.8)}$$

where, T is the time interval between tides, i.e. the tidal period. In practice, the power varies with time according to the difference in water levels across the barrage and the volume of water allowed to flow through the turbines. Also, the operating company would seek to optimise revenue by generating electricity during periods of peak-load demand when electricity prices are highest.

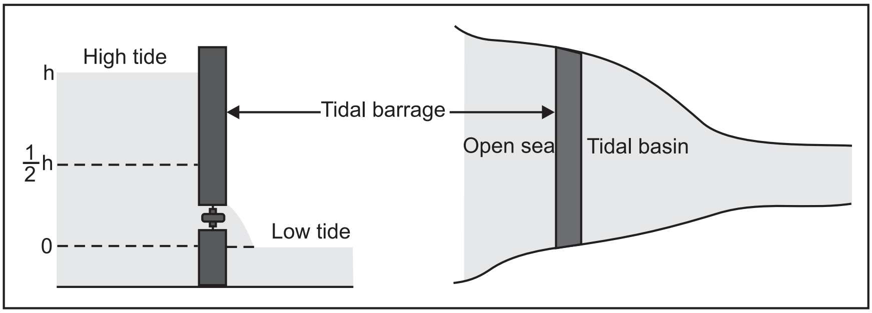



**Figure 13.3** Tidal barrage

## 13.5 Tidal resonance

The tidal range varies in different oceans of the world due to an effect known as tidal resonance. For example, the Atlantic Ocean has a width of about 4000 km and an average depth of about 4000 m, so the speed of a shallow water wave Eq. 13.3 is about $c = \sqrt{gh_0} \approx \sqrt{10 \times 4000} \approx 200$ m s$^{-1}$. The tidal frequency is about $2 \times 10^{-5}$ s$^{-1}$, so the wavelength is $\lambda = c/f \approx 200/(2 \times 10^{-5})$ m $\approx 10^4$ km. This is about twice the width of the Atlantic and so resonance occurs; the time taken for the shallow water wave to make the round trip, reflecting off both shores, is about the same as the tidal period, so the amplitude builds up.

The wave amplitude also increases on the continental shelf and can reach about 3 m at the shores. River estuaries can also exhibit large tidal resonance if the length and depth of the estuary are favourable. From Eq. 13.3 the time taken for a wave to propagate the length of the channel and back to the inlet is given by $t = 2L/c = 2L/\sqrt{gh_0}$ . If this time is equal to half the time between successive tides then the tidal range is doubled.

### 13.5.1 Tidal resonance in a uniform channel

For simplicity, consider a uniform channel of length L such that the end at x = 0 is open to the sea and the other end of the channel at x = L is a vertical wall. Suppose that the height of the incident tidal wave varies with time as hi (t) = a cos (ωt). We consider a travelling wave of the form:

$$h_i\,(x, t) = a \cos (kx - \omega t)$$

From the mass continuity Eq. 13.6, we have:

$$-\frac{\partial u_i}{\partial x} = \frac{1}{h_0}\frac{\partial h_i}{\partial t} = \frac{\omega a}{h_0}\sin(kx - \omega t)$$

Integrating with respect to x yields the velocity in the horizontal direction as:

$$u_i(x, t) = \frac{\omega a}{h_0 k}\cos(kx - \omega t)$$

In order to satisfy the boundary condition u = 0 at x = L (since there cannot be any flow across the barrier) we superimpose a reflected wave of the form:

$$u_r(x, t) = \frac{\omega a}{h_0 k}\cos(kx - \omega t)$$

The total velocity at x = L is given by $u(L, t) = u_i(L, t) + u_r(L, t) = \omega a/h_0 k\,[\cos(kL - \omega t) + \cos(kL + \omega t)] = 2\omega a/h_0 k \cos(kL)\cos(\omega t) = 0$. Hence $kL = \pi/2\,(2n + 1)$, and the lowest mode of oscillation (n = 0) is given by $kL = \pi/2$. Putting $k = 2\pi/\lambda$ we then obtain the minimum length of the channel as $L = \lambda/4$. The total height of the incident and reflected waves is:

$h(x, t) = h_i(x, t) + h_r(x, t) = a\cos(kx - \omega t) - a\cos(kx + \omega t) = 2a\sin(kx)\sin(\omega t)$.

At the end of the channel, x = L, the height is $h(L, t) = 2a\sin(wt)$, i.e. double that due to the incident wave. This causes the amplitude to build up with the result that the tidal range can be very large—in the River Severn estuary between England and Wales a range of 10–14 m is observed.

## 13.6 Kinetic energy of tidal currents

In particular locations (e.g. between islands) there may be strong tidal currents that transport large amounts of kinetic energy. In recent years various devices for extracting the kinetic energy have been proposed. These devices are essentially underwater versions of wind turbines and obey the same physical principles. In the majority of designs the axis of rotation of the turbine is horizontal and the device is mounted on the seabed or suspended from a floating platform. Before installation, the tidal currents for any particular location need to be measured to depths of 20 m or more in order to determine the suitability of the site. The first generation of prototype kinetic energy absorbers have been operated in shallow water (i.e. 20–30 m) using conventional engineering components. Later generations are likely to be larger, more efficient, and use specially designed low-speed electrical generators and hydraulic transmission systems.

## 13.7 Generation of tidal energy

Tidal power is extracted from the earth's oceanic tides; tidal forces are periodic variations in gravitational attraction exerted by celestial bodies. These forces create corresponding motions or currents in the world's oceans. The magnitude and character of this motion reflects the changing positions of the moon and sun relative to the earth, the effects of earth's rotation, and local geography of the sea floor and coastlines.

Tidal power is the only technology that draws on energy inherent in the orbital characteristics of the earth–moon system, and to a lesser extent in the earth–sun system. Other natural energies exploited by human technology originate directly or indirectly with the sun, including fossil fuel, conventional hydroelectric, wind, biofuel, wave and solar energy. Nuclear energy makes use of earth's mineral deposits of fissionable elements, while geothermal power taps the earth's internal heat, which comes from a combination of residual heat from planetary accretion (about 20 per cent) and heat produced through radioactive decay (80 per cent).

A tidal generator converts the energy of tidal flows into electricity. Greater tidal variation and higher tidal current velocities can dramatically increase the potential of a site for tidal electricity generation.

Because the earth's tides are ultimately due to gravitational interaction with the moon and sun and the earth's rotation, tidal power is practically inexhaustible and classified as a renewable energy resource. Movement of tides causes a loss of mechanical energy in the earth–moon system: this is a result of pumping of water through natural restrictions around coastlines and consequent viscous dissipation at the seabed and in turbulence. This loss of energy has caused the rotation of the earth to slow in the 4.5 billion years since its formation. During the last 620 million years the period of rotation of the earth (length of a day) has increased from 21.9 hours to 24 hours; in this period the earth has lost 17 per cent of its rotational energy. While tidal power may take additional energy from the system, the effect is negligible and would only be noticed over millions of years.

### 13.7.1 Categories of tidal power

Tidal power can be classified into three main types:

1. Tidal stream systems make use of the kinetic energy of moving water to power turbines, in a similar way to windmills that use moving air. This method is gaining in popularity because of the lower cost and lower ecological impact compared to barrages.

2. Barrages make use of the potential energy in the difference in height (or head) between high and low tides. Barrages are essentially dams across the full width of a tidal estuary, and suffer from very high civil infrastructure costs, a worldwide shortage of viable sites, and environmental issues.
3. Dynamic tidal power exploits a combination of potential and kinetic energy: by constructing long dams of 30–50 km in length from the coast straight out into the sea or ocean, without enclosing an area. Both the obstruction of the tidal flow by the dam—as well as the tidal phase differences introduced by the presence of the dam (which is not negligible in length as compared to the tidal wavelength)—lead to hydraulic head differences along the dam. Turbines in the dam are used to convert power (6–15 GW per dam). In shallow coastal seas featuring strong coast-parallel oscillating tidal currents (common in the UK, China and Korea), a significant water level differential (2–3 metres) will appear between both sides of the dam.

Modern advances in turbine technology may eventually see large amounts of power generated from the ocean, especially tidal currents using the tidal stream designs but also from the major thermal current systems such as the Gulf Stream, which is covered by the more general term marine current power. Tidal stream turbines may be arrayed in high-velocity areas where natural tidal current flows are concentrated such as the west and east coasts of Canada, the Strait of Gibraltar, the Bosporus, and numerous sites in Southeast Asia and Australia. Such flows occur almost anywhere where there are entrances to bays and rivers or between land masses where water currents are concentrated.

## 13.7.2 Tidal stream generators

### *Tidal versus wind turbines*

Tidal stream generators draw energy from currents in much the same way as wind turbines. As a relatively new technology, though first conceived in the 1970s during the oil crisis, the potential for power generation by an individual tidal turbine can be greater than that of similarly rated wind energy turbine. The higher density of water relative to air (water is about 800 times the density of air) means that a single generator can provide significant power at low tidal flow velocities compared with similar wind speed. Given that power varies with the density of medium and the cube of velocity, it is simple to see that water speeds of nearly one-tenth of the speed of wind provide the same power for the same size of turbine system; however this limits the application in practice to places where the tide moves at speeds of at least 2 knots (1 m/s) even close to neap tides. Furthermore, at higher speeds in a flow between 2 to 3 metres per second in seawater a tidal turbine can typically access four times as much energy per rotor swept area as a similarly rated power wind turbine.

## *Types of tidal stream generators*

Since tidal stream generators are an immature technology, no standard technology has yet emerged as the clear winner, but a large variety of designs are being experimented with, some very close to large scale deployment. Several prototypes have shown promise with many companies making bold claims, some of which are yet to be independently verified, but they have not operated commercially for extended periods to establish performances and rates of return on investments.

The European Marine Energy Centre categorises them under four heads although a number of other approaches are also being tried.

*Axial turbines:* These are close in concept to traditional windmills operating under the sea and have the most prototypes currently operating.

*Vertical and horizontal axis crossflow turbines:* Invented by Georges Darreius in 1923 and patented in 1929, these turbines that can be deployed either vertically or horizontally. Neptune Renewable Energy has developed Proteus which can be used to form an array in mainly estuarine conditions.
Oscillating devices: Oscillating devices do not have a rotating component, instead making use of aerofoil sections which are pushed sideways by the flow. Oscillating stream power extraction was proven with the omni- or bidirectional Wing'd Pump windmill.

*Venturi effect:* This uses a shroud to increase the flow rate through the turbine. These can be mounted horizontally or vertically.

## *Energy calculations*

*(a) Turbine power*

Various turbine designs have varying efficiencies and therefore varying power output. If the efficiency of the turbine 'ξ' is known the equation below can be used to determine the power output of a turbine.

The energy available from these kinetic systems can be expressed as:

$$P = \frac{\xi \rho A V^3}{2}$$

where, $\xi$ = the turbine efficiency.
$P$ = the power generated (in watts).

$\rho$ = the density of the water (seawater is 1025 kg/$m^3$).
A = the sweep area of the turbine (in $m^2$).
V = the velocity of the flow.

Relative to an open turbine in free stream, depending on the geometry of the shroud shrouded turbines are capable of as much as 3 to 4 times the power of the same turbine rotor in open flow.

### *Resource assessment*

While initial assessments of the available energy in a channel have focus on calculations using the kinetic energy flux model, the limitations of tidal power generation are significantly more complicated. For example, the maximum physical possible energy extraction from a strait is given by:

$$P = 0.221 \rho g \Delta H_{max}\ Q_{max}$$

where,

$\rho$ = the density of the water (seawater is 1025 kg/$m^3$)
g = gravitational acceleration (9.81 m/$s^2$)
$\Delta_{Hmax}$ = maximum differential water surface elevation across the channel
$Q_{max}$ = maximum volumetric flow rate through the channel

### *Potential sites*

As with wind power, selection of location is critical for the tidal turbine. Tidal stream systems need to be located in areas with fast currents where natural flows are concentrated between obstructions, for example at the entrances to bays and rivers, around rocky points, headlands or between islands or other land masses.

## 13.7.3 Environmental impacts

Tidal energy is a renewable resource of electricity and does not result in the creation of any emissions. In this way it is a benefit to the environment because its use reduces the demand on fuels such as coal and oil. As for environmental impacts, some of the non-monetary costs associated with barrage systems include destruction of habitat, interruption of organisms' travel routes, potential electromagnetic interference (in the case of species that can sense electric fields), and potential acoustic pollution. In addition, hydroelectric systems are well-known for killing fish, and the waste heat that ends up in the water reduces its capacity to store dissolved oxygen, harming not only fish, but all organisms in the affected area. Despite all this, such systems are attractive to many because of their reliance on existing technology and knowledge.

## 13.8 Advantages and disadvantages of tidal energy

Tidal wave energy is still a very niche technology with tidal barrages generating most of the electricity in a few power stations. Most of the tidal power plants using the modern tidal turbine technology are still in the pilot phase and generate negligible power. Tidal energy has many advantages and disadvantages with the cons of massive investments and long gestation time winning over the many pros of tidal power. Note tidal energy is a favourite for scientists and has been for a long time due to the almost limitless potential.

Like geothermal energy, however tidal energy is stuck in a low growth phase and faces a real possibility that it may not be anything but an esoteric source of energy. Tidal energy shares many of the same problems as geothermal energy does despite geothermal energy having a much longer history. Here is the list of the advantages and disadvantages of tidal energy.

### 13.8.1 Tidal power pros

1. *Renewable, non-polluting and carbon negative:* Tidal energy is completely renewable, does not lead to any pollution of the air and does not lead to any carbon emissions like fossil fuels.
2. *Predictable:* Tidal wave energy is very predictable as the tides rise with great uniformity. Other forms of renewable energy like solar and wind energy are intermittent in nature. The electricity supply is much more uniform and reliable in case of tidal power.
3. *No fuel:* Tidal power needs water for generation of electricity in its catchment area. It does not need fuel like thermal, gas or oil powered power stations.
4. *Low costs:* Once a tidal energy power plant starts running, its costs are extremely low.
5. *Long life:* A tidal barrage has a very long life of around 100 years which is much longer than that of even nuclear power plants. The long life implies that the life-cycle cost of a tidal energy power plant becomes very low in the long-term.
6. *High energy density:* The energy density of tidal energy is much higher than that of other forms of renewable energy like wind power.
7. *High load factor:* The load factor for solar and wind energy ranges from 15–40 per cent which is quite low compared to fossil fuel energy. Tidal energy has a load factor of almost 80 per cent which is equal to that of thermal power.

### 13.8.2 Tidal power cons

1. *High initial capital investment:* Tidal barrages require massive investment to construct a barrage or dam across a river estuary. This is comparable to construction of a massive dam for hydro power. This is perhaps the biggest disadvantage of this technology.
2. *Effect on marine life:* The operation of commercial tidal power stations has known to moderately affect the marine life around the power plant. It leads to disruption in movement and growth of fishes and other marine life and can also lead to increase in silt. Turbines can also kill fish passing through it.
3. *Immature technology:* Except for tidal barrage, the other forms of technology generating tidal or wave power are quite immature, costly and unproven.
4. *Long gestation time:* The cost and time over runs can be huge for tidal power plants leading to their cancellation just like that of the Severn barrage in the UK. Many of the tidal power stations like the gigantic plant being planned in Russia will never come to fruition because of the very long gestation time.
5. *Difficulty in transmission of tidal electricity:* Some forms of tidal power generate power quite far away from the consumption of electricity. Transportation of tidal energy can be quite cumbersome and expensive.
6. *Weather effects:* Severe weather like storms and typhoons can be quite devastating on the tidal power equipment especially those place on the sea floor.

Tidal energy like all other forms of energy suffers from both advantages and disadvantages. The tidal energy phase of development has made the cons outweigh the pros unlike other renewable energy forms like wind and solar energy. However innovative methods are being developing to harness tidal and wave energy which might prove to be a game changer and move tidal energy into the mainstream energy industry.

## 13.9 Wave energy

The waves on the surface of the sea are caused mainly by the effects of wind. The streamlines of air are closer together over a crest and the air moves faster. It follows from Bernoulli's theorem that the air pressure is reduced, so the amplitude increases and waves are generated. As a wave crest collapses the neighbouring elements of fluid are displaced and forced to rise above the equilibrium level (Fig. 13.4). The motion of the fluid beneath the surface decays exponentially with depth. About 80 per cent of the energy in a surface wave is contained within a quarter of a wavelength below the surface.

Thus, for a typical ocean wavelength of 100 m, this layer is about 25 m deep. We now derive an expression for the speed of a surface wave using intuitive physical reasoning. The water particles follow circular trajectories, as shown in Fig. 13.4.

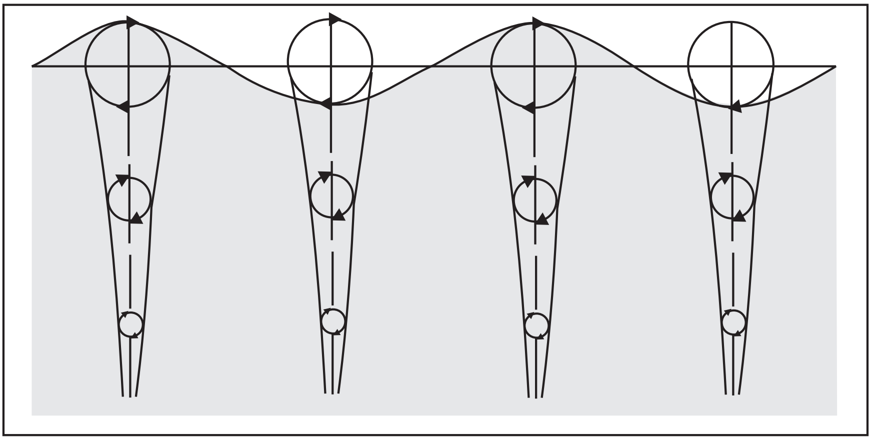


**Figure 13.4** Surface wave on deep water

Consider a surface wave on deep water and choose a frame of reference that moves at the wave velocity, c, so that the wave profile remains unchanged with time. Noting that the pressure on the free surface is constant (i.e. atmospheric pressure), Bernoulli's equation yields:

$$u_c^2 - u_t^2 - 2gh = 0 \qquad \text{... (13.9)}$$

where, $u_c$ is the velocity of a particle at a wave crest, $u_t$ is the velocity of a particle at a wave trough, and h is the difference in height between a crest and a trough. If r is the radius of a circular orbit and s is the wave period then we can put:

$$u_c = \frac{2\pi r}{\tau} - c, \quad u_t = \frac{2\pi r}{\tau} - c, \quad h = 2r. \qquad \text{... (13.10)}$$

Substituting for $u_c$, $u_t$ and h from Eq. 13.10 in Eq. 13.9, and putting $\lambda = c\tau$, we obtain the wave speed as:

$$c = \sqrt{g\lambda/(2\pi)} \qquad \text{... (13.11)}$$

It follows from Eq. 13.11 that the wave speed increases with wavelength, so that surface waves are dispersive. In practice the wave profile on the surface of the sea is a superposition of waves of various amplitudes, speeds, and wavelengths moving in different directions. The net displacement of the surface is therefore more irregular than that of a simple sine wave. Hence, in order for a wave power device to be an efficient absorber of wave energy in real sea conditions, it needs to be able to respond to random fluctuations in the wave profile. The total energy E of a surface wave per unit width of wave-front per unit length in the direction of motion is given by:

$$E = \frac{1}{2} rga^2 \qquad \text{... (13.12)}$$

The dependence of wave energy on the square of the amplitude has mixed benefits. Doubling the wave amplitude produces a fourfold increase in wave energy. However, too much wave energy poses a threat to wave power devices and measures need to be taken to ensure they are protected in severe sea conditions.

The power P per unit width in a surface wave is the product of E and the group velocity $c_g$, given by:

$$c_g = \frac{1}{2}\sqrt{g\lambda/(2\pi)} \qquad \text{... (13.13)}$$

Hence the incident power per unit width of wave-front is:

$$P = \frac{1}{4}\rho g a^2 \sqrt{g\lambda/(2p)} \qquad \text{... (13.14)}$$

In mid-ocean conditions the typical power per metre width of wave-front is 30–70 kW $m^{-1}$.

### 13.9.1 Wave power devices

Though the first patent for a wave power device was filed as early as 1799, wave power was effectively a dormant technology until the early 1970s, when the world economy was hit by a series of large increases in oil prices. Wave power was identified as one of a number of sources of alternative energy that could potentially reduce dependency on oil. It received financial support to assess its technical potential and commercial feasibility, resulting in hundreds of inventions for wave power devices, but most of these were dismissed as either impractical or uneconomic. The main concerns were whether wave power devices could survive storms and their capital cost. During the 1980s, publicly funded research for wave power virtually disappeared as global energy markets became more competitive. However, in the late 1990s interest in wave power technology was revived due to increasing evidence of global climate change and the volatility of oil and gas prices. A second generation of wave power devices emerged, which were better designed and had greater commercial potential. In general, the key issues affecting wave power devices are:

1. Survivability in violent storms
2. Vulnerability of moving parts to seawater
3. Capital cost of construction
4. Operational costs of maintenance and repair
5. Cost of connection to the electricity grid

We now describe various types of wave power device and examine how they operate and how they address the above challenges.

## *Spill-over devices*

TAPCHAN (TAPered CHANnel) is a Norwegian system in which sea waves are focused in a tapered channel on the shoreline. Tapering increases the amplitude of the waves as they propagate through the channel. The water is forced to rise up a ramp and spill over a wall into a reservoir about 3–5 m above sea level (Fig. 13.5). The potential energy of the water trapped in the reservoir is then extracted by draining the water back to the sea through a low-head Kaplan turbine. Besides the turbine, there are no moving parts and there is easy access for repairs and connections to the electricity grid. Unfortunately, shore-based TAPCHAN schemes have a relatively low power output and are only suitable for sites where there is a deep water shoreline and a low tidal range of less than about a metre. To overcome these limitations, a floating offshore version of TAPCHAN called Wave Dragon is under development, with an inlet span of around 200 m, to generate about 4 MW.

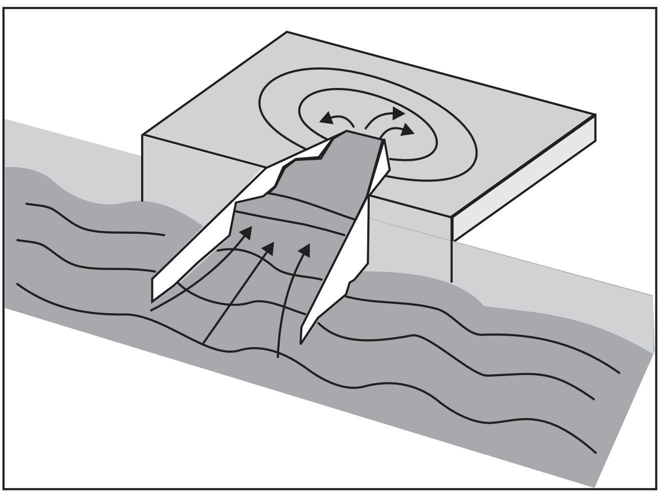


**Figure 13.5** TAPCHAN

### *Oscillating water columns*

The oscillating water column (OWC) uses an air turbine housed in a duct well above the water surface (Fig. 13.6). The base of the device is open to the sea, so that incident waves force the water inside the column to oscillate in the vertical direction. As a result the air above the surface of the water in the column moves in phase with the free surface of the water inside the column and drives the air turbine. The speed of air in the duct is enhanced by making the cross-sectional area of the duct much less than that of the column. A key feature of the OWC is the design of the air turbine, known as the Wells turbine. It has the remarkable property of spinning in the same direction irrespective of the direction of air flow in the column! Unlike conventional turbine blades, the blades in a Wells turbine are symmetrical about the direction of motion (Fig. 13.7). Relative to a blade, the direction of air flow is at a non-zero angle of attack $\alpha$. The net force acting on the blade in the direction of motion is then given by:

$$F = L \sin \alpha - D \cos \alpha \qquad \text{... (13.15)}$$

where, L and D are the lift and drag forces acting on the blade. It is clear from the force diagram in Fig. 13.7(b) that the direction of the net force is the same, irrespective of whether the air is flowing upwards or downwards inside the air column.

The shape of the blade is designed such as to maximise the net force on the blade and the operational efficiency of a Wells turbine is around 80 per cent. At low air velocities the turbine absorbs power from the generator in order to maintain a steady speed of rotation, whilst for large air velocities the air flow around the blades is so turbulent that the net force in the direction of motion of the blade becomes erratic and the efficiency is reduced. Two designs of shore-based OWCs are the Limpet (UK) and the Osprey (UK); generating about 0.5 and 1.5 MW, respectively. A prototype 0.5 MW Australian OWC scheme is also being developed, which uses a 40 m wide parabolic wave reflector to focus waves onto a 10 m wide shoreline OWC; the capital cost is 30 per cent higher but the output is increased by 300 per cent. A large floating OWC known as the Mighty Whale has been developed in Japan. It generates 110 kW but its primary role is as a wave breaker to produce calm water for fisheries and other marine activities.

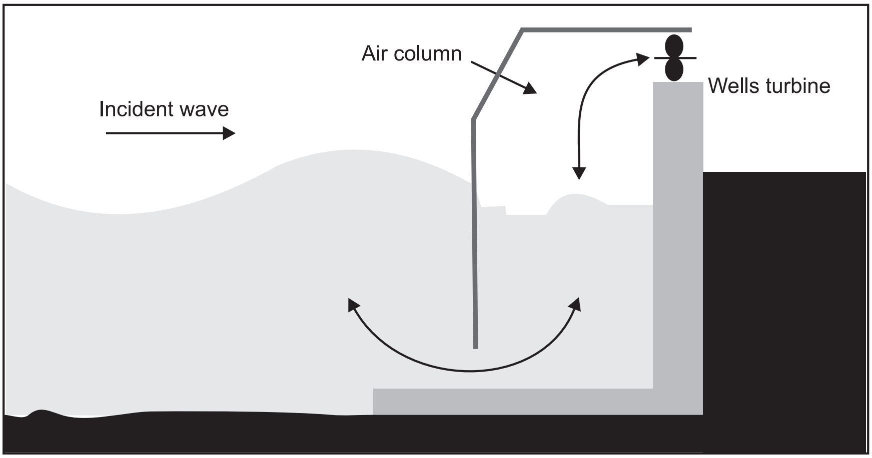



**Figure 13.6** Oscillating water column (OWC)

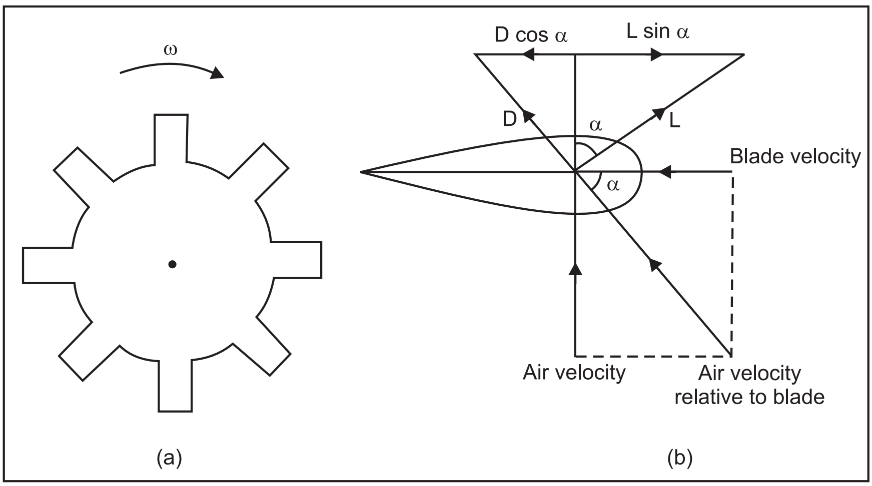



**Figure 13.7** Wells turbine: (a) plan view of blades and (b) velocity and force triangles in frame of reference of a blade

## *Submerged devices*

Submerged devices have the advantage of being able to survive despite rough sea conditions on the surface. They exploit the change in pressure below the surface when waves pass overhead: the pressure is increased for a wave crest but is decreased in the case of a wave trough. An example of this type of device is the Archimedes Wave Swing (AWS, Fig. 13.8). The AWS is a submerged air-filled chamber (the 'floater'), 9.5 m in diameter and 33 m in length, which oscillates in the vertical direction due to the action of the waves.

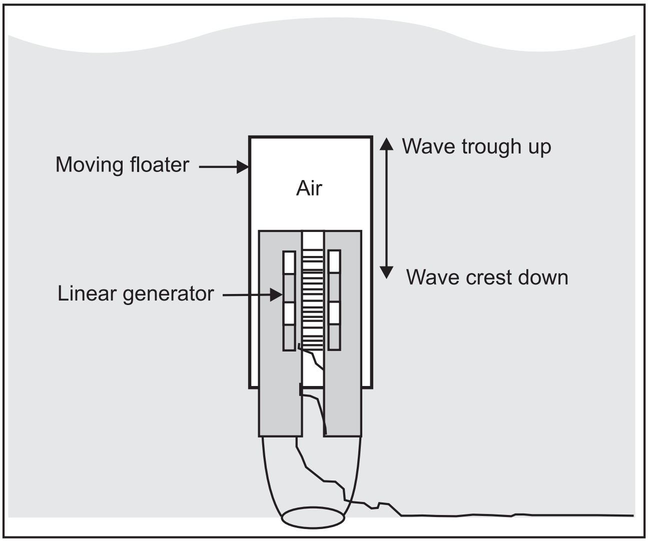



**Figure 13.8** Archimedes wave swing

The motion of the floater energises a linear generator tethered to the sea bed. The AWS has the advantage of being a 'point' absorber, i.e. it absorbs power from waves travelling in all directions, and extracts about 50 per cent of the incident wave power. Also, being submerged at least 6 m below the surface it can avoid damage in violent sea conditions on the surface. The device has the advantages of simplicity, no visual impact, quick replacement and cost effectiveness in terms of the power generated per kg of steel.

A pre-commercial pilot project off the coast of Portugal has three AWS devices and produces 8 MW. A fully commercial AWS system could involve up to six devices per kilometre and it is estimated that the global potential for AWS is around 300 GW.

## *Floating devices*

In the early 1970s public interest in wave power was stimulated by a novel device known as the Salter duck (Fig. 13.9). The device floated on water and rocked back and forth with the incident waves. The shape was carefully chosen such that the surface profile followed the circular trajectories of water particles, so that most of the incident wave energy was absorbed with only minimal reflection and transmission. Efficiencies of around 90 per cent were achieved in ideal conditions. The complete system envisaged a string of Salter ducks of several kilometres in total length parallel to a wave-front. A spinal column, of 14 m diameter, used the relative motion between each duck and the spine to provide the motive force to generate power.

The device was designed to be used in the Atlantic Ocean for wavelengths of the order of 100 m but never got beyond small-scale trials due to lack of funding in the 1980s when governmental support for wave power in the UK was dropped in favour of wind power. Nonetheless, the Salter duck provides a useful benchmark for comparing the efficiencies of all wave power devices.

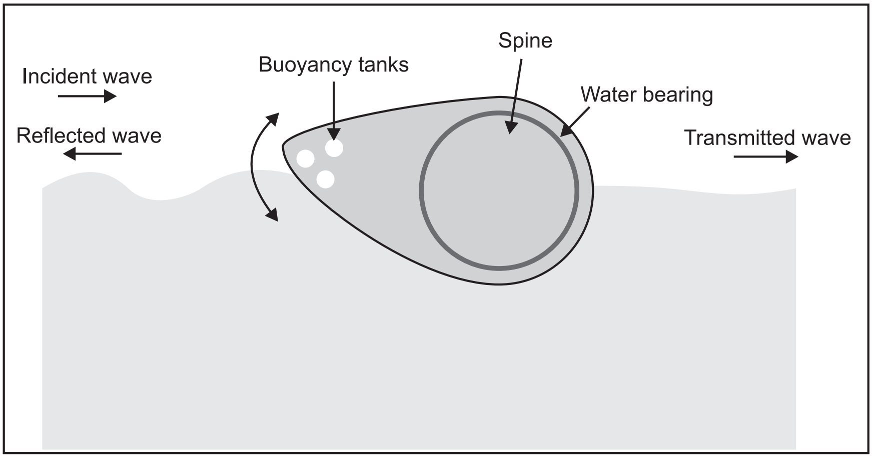



**Figure 13.9** Salter duck

A much more recent type of floating device is the Pelamis (Fig. 13.10). It is a semi-submerged serpentine construction consisting of series of cylindrical hinged segments that are pointed towards the incident waves. As waves move along the device, the segments rock back and forth and the relative motion between adjacent segments activates hydraulic rams that pump high pressure oil through hydraulic motors and drive electrical generators. A three-segment version of Pelamis is 130 m long and 3.5 m in diameter and generates 750 kW. The combination of great length and small cross-section to the incident waves provides good protection to large amplitude waves. Three Pelamis devices are due to be installed 5 km off the coast of Portugal and it is estimated that about 30 machines per square kilometre would generate about 30 MW. In order to prevent unwanted interference effects, the devices are spaced apart by about 60–90 m.

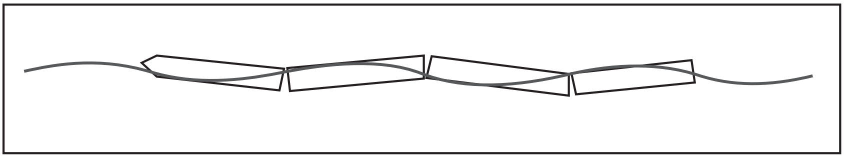


**Figure 13.10** Pelamis

## 13.9.2 Environmental impact, economics and prospects of wave power

As with most forms of alternative energy, wave power does not generate harmful greenhouse gases. Opposition to shore-based sites could be an issue in areas of scenic beauty, on account of the visual impact (including the connections to the electricity transmission grid) and the noise generated by air turbines in the case of oscillating water columns. The visual impact is much less significant for offshore devices but providing cables for electricity transmission to the shore is an added cost.

The global potential of wave power is very large, with estimates of 1–10 TW. Around the UK the Department of Trade and Industry (DTI) estimated (2001) a potential of about 6 GW from wave power. The main challenges for the implementation of wave power are to reduce the capital costs of construction, to generate electricity at competitive prices, and to be able to withstand extreme conditions at sea. Wave power is generally regarded as a high risk technology. Moving to shore-based and near-shore devices reduces the vulnerability to storms but the power available is less than that further out at sea. Even the largest floating devices are vulnerable in freak storms: every 50 years in the Atlantic Ocean there is a wave with an amplitude about ten times the height of the average wave, so any device must be able to withstand a factor of a hundred times the wave energy. Measures to combat such conditions such as submerging the devices can provide an effective means of defence but add to the cost of the system. Another factor to consider is that the frequency of incident sea waves is only about 0.2 Hz, much lower than the frequency of 50–60 Hz for electricity transmission. Though this not a difficult electrical engineering problem, the challenge is to find cost-effective solutions. Wave power is beginning to look competitive in certain niche markets, especially in remote locations where electricity supplies are expensive. However, it is likely to take one or two decades to gather sufficient operational experience for wave power to compete with other alternative energy technologies. In the long-term as fossil fuel reserves become scarce, and concerns over global warming increase, forecasts of an eventual global potential for wave power to provide about 15 per cent of total electricity production do not seem unreasonable, as part of a diverse mix of alternative energy sources.

## 13.10 Ocean energy

Oceans cover more than 70 per cent of earth's surface, making them the world's largest solar collectors. The sun's heat warms the surface water a lot more than the deep ocean water, and this temperature difference creates thermal energy. Just a small portion of the heat trapped in the ocean could power the world. Ocean thermal energy is used for many applications, including electricity generation. There are three types of electricity conversion systems: closed-cycle, open-cycle, and hybrid. Closed-cycle systems use the ocean's warm surface water to vapourise a working fluid, which has a low-boiling point, such as ammonia. The vapour expands and turns a turbine. The turbine then activates a generator to produce electricity. Open-cycle systems actually boil the seawater by operating at low pressures. This produces steam that passes through a turbine/generator. And hybrid systems combine both closed-cycle and open-cycle systems.

Ocean mechanical energy is quite different from ocean thermal energy. Even though the sun affects all ocean activity, tides are driven primarily by the gravitational pull of the moon, and waves are driven primarily by the winds. As a result, tides and waves are intermittent sources of energy, while ocean thermal energy is fairly constant. Also, unlike thermal energy, the electricity conversion of both tidal and wave energy usually involves mechanical devices.

A barrage (dam) is typically used to convert tidal energy into electricity by forcing the water through turbines, activating a generator. For wave energy conversion, there are three basic systems: channel systems that funnel the waves into reservoirs; float systems that drive hydraulic pumps; and oscillating water column systems that use the waves to compress air within a container. The mechanical power created from these systems either directly activates a generator or transfers to a working fluid, water or air, which then drives a turbine/generator.

Sufficient temperature gradients are found in equatorial and tropical regions. The surface temperatures there can reach values between 25° and 30ºC in a layer 100 to 200 m thick and their seasonal variations are not markedly different. The raw solar energy resource captured annually by the oceans is enormous, in the order of $400 \times 10^{15}$ kWh (i.e. ~ 45,000 TW).

Considering the global output of all the deep cold currents (30 $Mm^3/s$) and the fact that conceivable thermodynamic machines require a very high discharge of cold water (about 2 $m^3/s$ per MW) and weak conversion efficiency in the order of 3 per cent (principally due to the small difference in temperature between the hot and cold sources), we reach a maximum annual potential of 80,000 TWh, which is renewable.

### 13.10.1 Ocean thermal energy conversion

1. The thermodynamic converters may be of two types: open or closed cycles.
2. The open cycle machines use seawater directly and make it possible to avoid exchangers that are very cumbersome and risk being clogged from the effect of biofouling (growth of micro-organisms). The principle consists of having two turbines work in a belt of very low pressure (2 to 3 kPa or 20 to 30 mbar) created with vacuum pumps. The water from the hot source, at such pressures, vapourises and drives the turbine, then condenses on contact with the cold source. The freshwater obtained by condensation can then be used as a value added by-product. The major disadvantage of the open cycle resides in the large dimensions of the low pressure turbine. To produce 1 MW, a turbine diameter of 8 m is required.
3. The closed cycle, for its part, at the price of using a fluid of lower boiling point, such as ammonia, and exchangers with a large surface, allows the use of a turbine of smaller dimension (diameter 1 m for 1 MW).
4. The exchangers should have surfaces of the order of 10,000 $m^2$ per MW and resist corrosion and biofouling. Materials used are titanium and aluminium. The battle against biofouling requires, if we want to avoid using chemical products (chlorine, for example), almost continuous mechanical washing.
5. If these methods can be put to long-term use, ocean thermal energy conversion (OTEC) power stations could first be used in islands in tropical and equatorial regions, where basic electricity production from fossil sources is increasingly expensive.

Figure 13.11 shows the ocean thermal energy conversion: open cycle and Fig. 13.12 shows the ocean thermal energy conversion: close cycle.

### 13.10.2 Good areas for exploiting tidal energy

Tidal range may vary over a wide range (4.5–12.4 m) from site to site. A tidal range of at least 7 m is required for economical operation and for sufficient head of water for the turbines. Traditional tidal electricity generation involves the construction of a barrage across an estuary to block the incoming and outgoing tide. The dam includes a sluice that is opened to allow the tide to flow into the basin; the sluice is then closed, and as the sea level drops, the head of water (elevated water in the basin) using traditional hydropower technology, drives turbines to generate electricity. Barrages can be designed to generate electricity on the ebb side or flood side or both.

There are many ways to generate electricity from the huge power of the tides: building tidal barrages, exploiting naturally occurring tidal streams, and tidal fences (a scaled down version of the tidal barrage). However, all of these techniques require huge financial investment and have very long pay back periods. In addition there are well documented negative environmental effects which have to be considered.

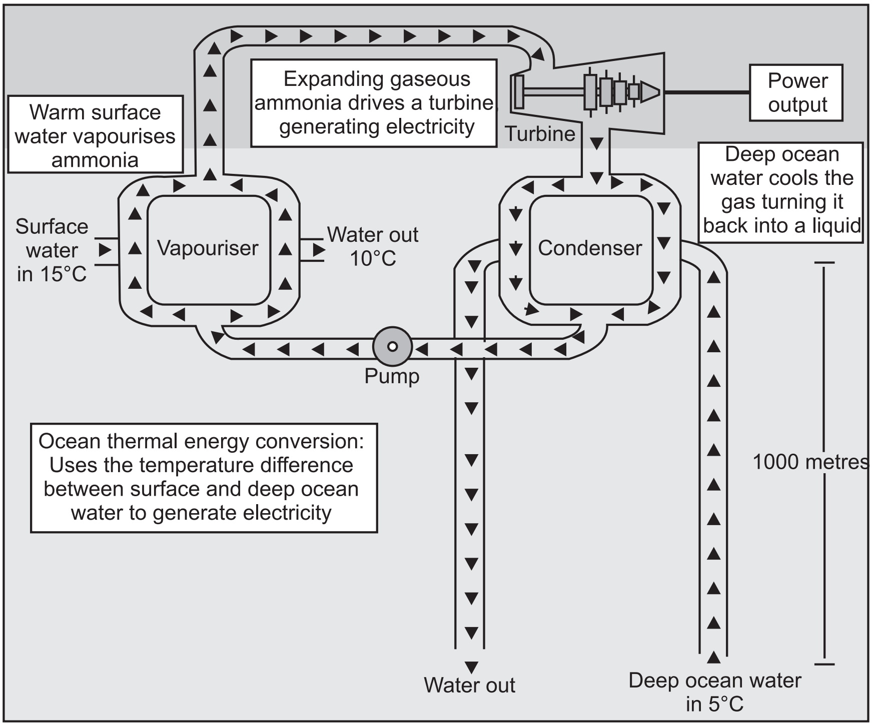



**Figure 13.11** Ocean thermal energy conversion: Open cycle

The technology required to convert tidal energy into electricity is very similar to the technology used in traditional hydroelectric power plants. The first requirement is a dam or 'barrage' across a tidal bay or estuary. The best tidal sites are those where a bay has a narrow opening, thus reducing the length of dam which is required. At certain points along the dam, gates and turbines are installed. When there is an adequate difference in the elevation of the water on the different sides of the barrage, the gates are opened. This ‘hydrostatic head’ that is created, causes water to flow through the turbines, turning an electric generator to produce electricity. Electricity can be generated by water flowing both into and out of a bay. As there are two high and two low tides each day, electrical generation from tidal power plants is characterised by periods of maximum generation every twelve hours, with no electricity generation at the six-hour mark in between. Alternatively, the turbines can be used as pumps to pump extra water into the basin behind the barrage during periods of low electricity demand. This water can then be released when demand on the system its greatest, thus allowing the tidal plant to function with some of the characteristics of a ‘pumped storage’ hydroelectric facility.

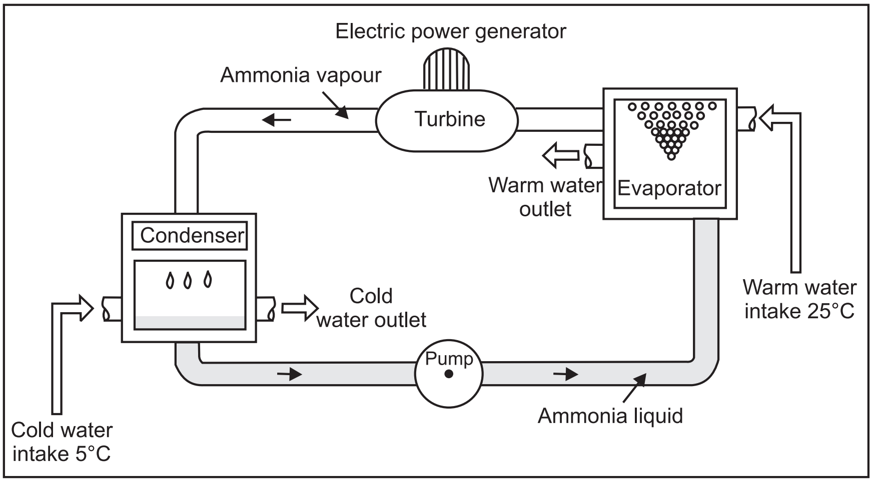



**Figure 13.12** Ocean thermal energy conversion: Close-cycle

Although the technology required to harness tidal energy is well established, tidal power is expensive, and there is only one major tidal generating station in operation. This is a 240 MW station at the mouth of the La Rance river estuary in France.

Studies have been undertaken to examine the potential of several other tidal power sites worldwide. It has been estimated that a barrage across the Severn River in western England could supply as much as 10 per cent of the country’s electricity needs (12 GW). Similarly, several sites in the Bay of Fundy, Cook Inlet in Alaska, and the White Sea in Russia have been found to have the potential to generate large amounts of electricity.

### 13.10.3 Costs of tidal energy

Tidal power is a form of low-head hydroelectricity and uses familiar low-head hydroelectric generating equipment, such as has been in use for more than 120 years. The placement of the impoundment offshore, rather than using the conventional 'barrage' approach, eliminates environmental and economic problems that have prevented the deployment of commercial-scale tidal power plants.

Offshore tidal power generators use familiar and reliable low-head hydroelectric generating equipment, conventional marine construction techniques, and standard power transmission methods.

Electricity can be generated by water flowing both into and out of a bay. As there are two high and two low tides each day, electrical generation from tidal power plants is characterised by periods of maximum generation every six hours. Alternatively, the turbines can be used as pumps to pump extra water into the basin behind the barrage during periods of low electricity demand. This water can then be released when demand on the system is at its greatest. This allows the tidal plant to function with some of the characteristics of a pumped storage hydraulic facility. In order to produce practical amounts of electricity, a difference between high and low tides of at least 5 metres is required.

### 13.10.4 Devices for tidal energy conversion

Tidal energy exploits the natural ebb and flow of coastal tidal waters caused principally by the interaction of the gravitational fields of the earth, moon and sun. The fast sea currents are often magnified by topographical features, such as headlands, inlets and straits, or by the shape of the seabed when water is forced through narrow channels. The tidal stream devices which utilise these currents are broadly similar to submerged wind turbines and are used to exploit the kinetic energy in tidal currents. Due to the higher density of water, this means that the blades can be smaller and turn more slowly, but they still deliver a significant amount of power. To increase the flow and power output from the turbine, concentrators (or shrouds) may be used around the blades to streamline and concentrate the flow towards the rotors.

There are four main types of tidal energy convertors (TEC):

1. *Horizontal axis turbine:* This device extracts energy from moving water in much the same way as wind turbines extract energy from moving air. Devices can be housed within ducts to create secondary flow effects by concentrating the flow and producing a pressure difference.

2. *Cross-axis turbine:*
   (a) *Vertical:* This device extracts energy from moving in a similar fashion to that above, however the turbine is mounted on a vertical axis.
   (b) *Horizontal:* This device is essentially a vertical cross axis turbine orientated horizontally. This turbine configuration allows for deployment in shallow water.
3. *Oscillating hydrofoil:* A hydrofoil attached to an oscillating arm and the motion is caused by the tidal current flowing either side of a wing, which results in lift. This motion can then drive fluid in a hydraulic system to be converted into electricity.
4. *Enclosed tips (venturi):* By housing the device in a duct, this has the effect of concentrating the flow past the turbine. The funnel-like collecting device sits submerged in the tidal current. The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine.
5. *Other designs:* This covers those devices with a unique and very different design to the more well-established types of technology or if information on the device's characteristics could not be determined.

# 14
# Geothermal power generation

## 14.1 Introduction

Geothermal comes from the Greek words *'geo'* which means earth and *'therme'* which means heat. So, geothermal energy means energy or power extracted from beneath the earth. The energy inside the earth was formed by the decay of minerals and forests several years ago. Traditionally, it was used for bathing and heating purposes but today it is also used for generating electricity. Geothermal energy is called renewable source of energy because heat is continuously produced inside the earth.

This heat is brought to the near-surface by thermal conduction and by intrusion into the earth's crust of molten magma originating from great depth. As groundwater is heated, geothermal energy is produced in the form of hot water and steam.

Geothermal energy is produced inside the earth's surface. The earth's layer consists of innermost layer called iron core which itself has two layers: solid iron core and an outer core made of hard rock, called magma, mantle which surrounds the core and the outermost layer called crust which forms oceans and continents. When magma comes close to the earth's surface, i.e. crust it heats up the groundwater which gets trapped in porous rocks. They may also flow along faults and fractured rock surfaces. Now these hydrothermal resources have two ingredients: water (hydro) and heat (thermal). When these hydrothermal resources occur naturally these are called geothermal reservoirs. Various tools and techniques are used nowadays to detect geothermal reservoirs.

*Geothermal energy existence:* Geothermal energy exists in the form of: (i) volcanoes, (ii) hot springs, and (iii) geysers.

Geothermal energy is clean and sustainable and environment friendly. It may be noted that the so called 'ring of fire' of the earth envelopes the Pacific rim. Though there are over 300 hot springs sites in India, this form of energy is yet to be tapped. In USA, California generates highest amount of electricity through geothermal energy.

*Future of geothermal energy:* The future of geothermal energy depends on three factors: its demand, supply and its competitiveness among other renewable resources in terms of cost, availability, reliability etc. Demand for geothermal energy is going to increase and increase with the increase in the population and extinction of other non-renewable sources. Moreover, today government also support the resources which are cleaner and do not spoil the environment. Supply of geothermal energy is limited and confined to certain areas only. The entire resource of geothermal energy is fairly bigger than that of coal, oil and gas. Geothermal energy can be made more widely available if the methods and technologies used to extract it are improved. Geothermal energy is still not explored fully. Several miles below the earth surface is hot, dry rock being heated by the molten magma directly below it.

## 14.2 Geothermal fluid

Geothermal fluid—a hot, sometimes salty, mineral-rich liquid and/or vapour—is the carrier medium that brings geothermal energy up through wells from the subsurface to the surface. This hot water and/or steam is withdrawn from a deep underground reservoir and isolated during production, flowing up wells and converting into electricity at a geothermal power plant. Once used, the water and condensed steam is injected back into the geothermal reservoir to be reheated. It is separated from groundwater by thickly encased pipes, making the facility virtually free of water pollution.

A resource that uses an existing accumulation of hot water or steam is known as a ‘hydrothermal’ resource. While several other types of geothermal resources exist, all producing geothermal plants in the United States use hydrothermal resources.

Characteristics of the geothermal fluid, including temperature, chemistry, and non-condensable gas content (NCG), can influence power plant design.

### 14.2.1 Temperature

Each power plant is designed to optimise the use of the heat supplied by the geothermal fluid. Underground heat can reach thousands of degrees, as shown in Fig. 14.1.

Geothermal fluids suitable for hydrothermal electricity production generally occupy a range of 200°F, 93°C (low temperature) to 400°F, 204°C (high temperature). The type of conversion technology and size of various components, such as heat exchangers and cooling towers, is determined by the temperature of the carrier medium. As the temperature of the resource goes up, the efficiency of the power system increases.

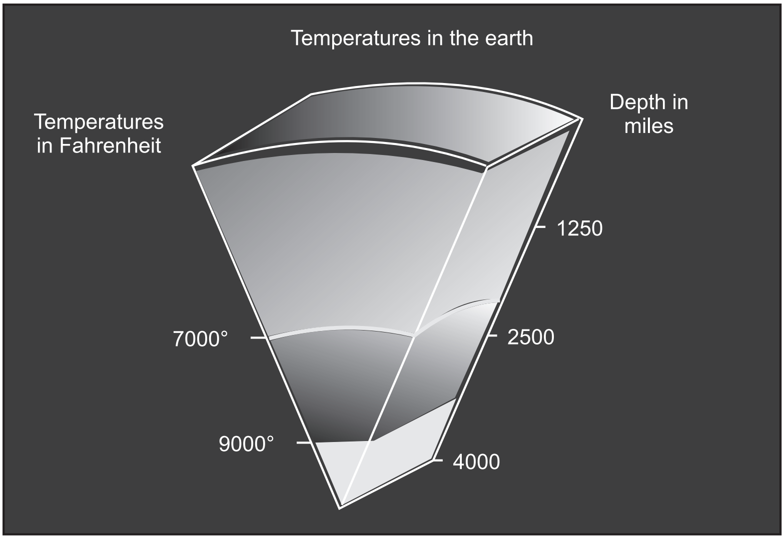



**Figure 14.1** Earth's temperatures

## 14.2.2 Chemistry

Several chemical characteristics are addressed at the beginning of the power plant design phase, including the NCG content, corrosiveness, and geothermal liquid scaling potential, which may require additional equipment. While flash and dry steam plants may or may not produce gases as part of the conversion process, binary facilities, which function in closed loop systems, produce near zero gas emissions.

### *Non-condensable gases*

Geothermal fluids contain entrained non-condensable gases (NCGs) that may not be easily injected back into the reservoir. These gases, which accumulate in the condenser, can decrease heat transfer and raise turbine back-pressure, thereby lowering turbine performance. Steam is sometimes used in ejectors to remove NCGs, but this reduces the amount of steam available for use in the turbines.

Typically, either steam jet ejectors, vacuum pumps or a combination are used to remove NCGs. The system's 'parasitic load'—as steam in ejectors or electricity that operates vacuum pumps—is reduced through recent improvements in vacuum systems. Reductions in parasitic load will increase the overall efficiency of the system. When parasitic load is decreased, more energy can be used to create electricity. Steam jet ejectors produce lower plant efficiencies but cost less than vacuum pumps. Because jet ejectors require steam supply, the quantity of steam available for producing electricity is reduced compared with the quantity available using vacuum pumps.

Vacuum pumps tend to be more expensive and complex, but are more energy efficient. Therefore a cost-benefit analysis will best determine how and to what extent non-condensable gases should be removed from a geothermal system.

Though some geothermal fluids contain non-condensable gases, emissions of each of these are significantly lower than those found at fossil fuel power plants. Typically less than 5 per cent of cooling tower non-condensable gases contain regulated toxic substances, such as hydrogen sulphide and mercury, discussed below. Even in those reservoirs with regulated gases, developers have no trouble meeting California's stringent standards.

### *Hydrogen sulphide*

Hydrogen sulphide ($H_2S$) is a colourless gas that is harmless in small quantities, but is often regarded as an annoyance due to its distinctive rotten-egg smell. Anthropogenic (man-made) sources of hydrogen sulphide account for approximately 5 per cent of total hydrogen sulphide emissions. $H_2S$ emissions vary with type and size of the plant and with the chemical quality of the resource.

During drilling and certain plant maintenance activities at some reservoirs, hydrogen sulphide gases can pose a worker safety issue. Appropriate plant design and drilling safety procedures developed through oil and gas and geothermal experience are therefore implemented, and standards and procedures are imposed by state and federal regulatory agencies. In addition, $H_2S$ is abated at some geothermal power plants where necessary to meet air quality standards. The two most commonly used vent gas hydrogen sulphide abatement systems are the Stretford and LO-CAT. Both systems convert over 99.9 per cent of the hydrogen sulphide from geothermal non-condensable gases to elemental sulphur, which can then be used as a soil amendment and fertiliser feedstock. The cost to transport and sell the sulphur as a soil amendment is about equal to the revenue gained from the transaction.

### *Mercury*

The mercury abatement measures are already in place at most geothermal facilities where mercury is present (though mercury is not present at every geothermal resource). Abatement measures that reduce hydrogen sulphide also reduce mercury: after hydrogen sulphide is removed from geothermal steam, the gas is run through a mercury filter that absorbs mercury from the gas. After removing mercury, the sulphur created from the abatement process can then be used as an agricultural product.

The rate of mercury abatement within a facility, which varies according to the efficiency of the activated carbon mercury absorber, is typically near 90 per cent, and is always efficient enough to ensure that the sulphur by-product is not hazardous. The activated carbon media is changed out periodically and is disposed of.

### *Corrosion*

At some resource sites, geothermal liquids can gradually wear away power plant materials by chemical action, a process known as corrosion. Corrosion is particularly problematic at mineral rich resource areas, such as the Salton Sea. Much like rust corrodes a nail, geothermal liquids can corrode the metal components of a power plant (pipes, heat exchanger, tanks, etc.) if resistant materials are not used. Corrosion resistant materials such as stainless steel or titanium can be substituted for more corroded carbon steel. Protective coatings can also be applied to carbon steel at a lower cost than corrosion resistant steel alloys or titanium. Though figures vary widely, using corrosion-resistant materials can reduce costs by around 0.25 cents per kWh.

### *Scaling*

At some resource locations, dissolved elements produce scaling. Scaling, a type of precipitation, occurs directly on a surface such as a heat transfer surface or pipe wall. Scaling results in dissolved materials that separate from solution, sometimes remaining suspended as small particles or attaching to a solid surface such as a pipe wall. Silica, a sand-like material, is the most common substance that scales out. Other common materials include metallic carbonates and sulphides.

Scaling can be induced by temperature and pH changes. When flashing a liquid to produce steam in separators, the carbon dioxide ($CO_2$) originally dissolved in the geothermal liquid is naturally emitted in limited amounts. This creates a positive feedback loop, because the pH increases as a result of the $CO_2$ emission, which results in further scaling of dissolved liquids.

Scaling can be dealt with in a variety of ways. A developer can reduce the heat captured from the geothermal liquid (thereby reducing plant efficiency), add scaling inhibitors or acidify the geothermal liquid to maintain minerals in solution. More complex equipment may be required to clean the geothermal liquid and control mineral precipitation.

Methods of scale control have improved in recent years, with technologies such as the crystallizer–reactor–clarifier and pH Mod now successfully used at geothermal facilities. One of the advantages of the binary system is avoided by scaling. By maintaining the geothermal water under pressure and injecting it at an elevated temperature (above 160°F or 71°C), the dissolved chemical constituents are maintained in solution. This mitigates/prevents scaling of heat exchangers, wells, and piping.

### 14.2.3 Injection

Hot water and steam gathering systems are the network of pipelines connecting the power plant with production and injection wells. The size and cost of a steam gathering system can be influenced by some or all of the following: site topography, slope stability, size and spread of the steam field, and temperature and pressure of the resource. Production wells bring the geothermal water to the surface to be used for power generation, while injection wells return the geothermal water and steam condensate back into the geothermal system to be used again. In order to maintain a geothermal system and ensure the continued availability of a resource, geothermal liquids must be injected back into the system. Benefits of injection include enhanced recovery and safe disposal of geothermal fluids, reduced possibility of subsidence, and an increased operational lifetime of the reservoir. When geothermal water is injected, it runs through pipes and cools to a typical injection temperature of 180°F (82°C). If the cooled geothermal liquid is injected too close to a production well, the resource may cool. If, however, the water is injected too far from the geothermal reservoir, it will not sufficiently replenish the system and reservoir pressure may decline.

## 14.3 Power plant basics

Like all conventional thermal power plants, a geothermal plant uses a heat source to expand a liquid to vapour/steam. This high pressure vapour/steam is used to mechanically turn a turbine-generator. At a geothermal plant, fuel is geothermal water heated naturally in the earth, so no burning of fuel is required.

At many power plants, a steam turbine is used to convert the thermal energy extracted from pressurised steam into useful mechanical energy. Mechanical energy is then converted into electricity by the generator. Geothermal plants rely upon one or a combination of three types of conversion technology—

binary, steam, and flash—to utilise the thermal energy from the hot subsurface fluids and produce electricity.

Each of these processes is described in greater detail in the next section of this chapter, 'conversion technologies'.

After the thermal energy has been used to turn the turbine, spent steam is condensed back to a liquid and injected into the ground where it is reused in the geothermal system, prolonging the lifetime of a geothermal plant. Electricity is then transported by transmission lines into the regional grid.

### 14.3.1 Design and construction

As one expert notes in his survey of geothermal power plant technology, 'power generation from geothermal resources has been around for more than 100 years; yet there continue to be advancements made that improve resource utilisation, reliability, and economics'. Although funds for research and development have tended to focus on less advanced subsurface exploration techniques, new surface developments also shape the industry. Surface technology advances improve the viability of a geothermal resource and often provide short-term payback.

A power plant typically requires 6–9 months to build once the shovel hits the ground and construction begins. However, when the time needed for exploration, discovery, permitting, and other hurdles is taken into account, the entire geothermal development process can last anywhere from 3 to 7 years or more.

A geothermal developer considers a number of factors when building a plant, particularly related to cost and the long-term viability of a project. Power plant designers must find the optimal size of power plant equipment and choose the best-suited technologies and construction materials that deal with site and resource specifics. Resource characteristics and those of the geothermal carrier medium vary in temperature, chemistry, and permeability. Site characteristics vary depending upon weather conditions, water availability, and geological factors such as ground and slope stability.

### 14.3.2 Recent power plant developments—turbines

Turbine efficiencies have improved in recent years, increasing as much as ten percentage points. At The Geysers, for example, turbines have been designed to more appropriately match current steam conditions and to utilise more efficient and reliable turbine blade technology. Turbines at steam plants now benefit from longer lasting stage blades and a variety of other improvements.

## 14.3.3 Factors affecting plant size

### *Economies of scale*

Though the size of a power plant is determined primarily by resource characteristics, these are not the only determining factors. In some cases, a larger power plant proves more cost-effective than a smaller version due to economies of scale. A ten megawatt plant, for example, usually requires all the elements of a 50 megawatt plant. And though a few small plants are capable of running virtually by themselves with monitoring, a geothermal plant usually requires a minimum number of people to run, whether the plant is 50 or 100 MW.

Certain other construction, operation and maintenance costs must be borne independently of the project's capacity. Remote areas tend to have little existing infrastructure, so many geothermal power plants will require excavation, road building, and electric, phone and other connections. Transmission costs can also be significant regardless of power plant size.

### *Transmission*

Because geothermal resources cannot be transported distances over more than a few miles without heat loss, geothermal plants must be built at the site of the reservoir and rely upon transmission systems. If new transmission lines are needed to access the regional grid, high costs can sometimes prohibit geothermal development. While larger transmission systems are traditionally more expensive than smaller versions, economies of scale still apply. For example, companies must negotiate and pay for easements and rights-of-way (ROW) if transmission lines cross private or public lands.

Transmission costs also depend upon topography, slope stability, site accessibility, and aesthetic sensitivities. The length of transmission lines from geothermal facilities to the grid delivery point can vary significantly.

The voltage size of transmission systems can vary considerably as well, depending upon the power involved—from a low of 60 kilovolts (kV) to a high of 230 kV. A typical transmission line averages around 100 kV.

### *Resource uncertainty*

All aspects of the power production process must be taken into account when choosing the megawatt capacity of a power plant, and this may lead to the preference for a smaller sized plant—regardless of economies of scale. Because the ultimate reservoir capacity characteristics and response to production can be uncertain at the start of a project, developers may opt to begin small and then gradually expand the use of the resource rather than risk: (i) overusing the resource, and (ii) spending money on costly power plant infrastructure only to find resource recovery is lower than expected due to misunderstandings of subsurface resource characteristics. In the past, some oversized projects have faced serious problems due to overuse.

#### *Other factors promoting small size*

Large plants can take longer to permit than their smaller counterparts and generally require longer environmental reviews. The production tax credit (PTC), a credit awarded for renewable energy generation, offers yet another incentive for developers to construct small plants. To be eligible for the PTC, developers' plants must begin operation within a challengingly short timeframe. The PTC, which has been cited by many experts as the most important policy needed to move the geothermal industry forward, incentivises developers to create smaller plants with consequently smaller lead times.

One final factor promoting smaller units could come from a stipulation in a plant's power purchase agreement (PPA)—the contract to buy the electricity generated by a power plant. A PPA could require a company to first develop a modest number of megawatts, and then gradually work up to a larger output.

#### *Average size*

Considering these factors, some experts cite an economically viable geothermal power plant at 20 MW. In practice, plants in the states range from less than 1 MW to just over 100 MW.

### 14.3.4 Raw materials

Geothermal power plants require a variety of raw materials. Some can be difficult and costly to obtain due to competition for limited resources. The cost of steel—which account for 10–20 per cent of the cost of a geothermal power system—has increased substantially in recent years, particularly due to a demand from China. The steel needs of the oil and gas industry also increase worldwide demand. Other raw materials critical to geothermal development include concrete, oil, fuel (for a drill rig) and lumber. Some of these costs have doubled in recent years.

## 14.4 Holistic design approach for geothermal binary power plants with optimised net electricity provision

The contribution of geothermal binary power plants to the energy system is based on the provision of net electricity. That is defined by the produced gross electricity from which the auxiliary power to run power consuming components in the different parts of the plant must be deduced. In contrast to other thermal power plants the ratio of auxiliary power to gross electricity can significantly vary in geothermal binary power plants depending on site-specific conditions. It typically lies in the range of 30–50 per cent but can be also higher depending on the site-specific energetic effort to deliver the geothermal fluid from the reservoir or the effort for the recooling of the conversion cycle. In order to optimise the provision of net electricity at a specific site it is hence important to consider the different characteristics of gross electricity production and auxiliary power consumption. The chapter will therefore introduce a geothermal-specific, holistic design approach in which not only parameters, which characterise the quality of single plant components, but also site-specific reservoir and ambient conditions are considered. With the presented methodology, in contrast, it is possible to realise geothermal binary power plants with a higher net electricity output based on existing technology.

Binary power plants are used to produce power from low to medium temperature heat sources. Since the predominant part of the worldwide geothermal potential is based on a temperature level between 100° and 200°C, binary power plants will play a more and more important role for geothermal power generation in the future. The role which different power plant technologies or energy sources play in the electricity mix is typically measured by the total installed power capacity. However, the real contribution of power plants is their net electricity output which is defined by the produced gross electricity from which the auxiliary power to run the power consuming components in a plant must be deduced.

Geothermal binary power plants contain not only the power unit on the surface but also the geothermal fluid loop to deliver the fluid from the reservoir (Fig. 14.2). Therefore, the power consuming components of such plants are in the geothermal fluid loop (such as the downhole pump), in the binary power unit (such as the feed pump), and the recooling system (such as cooling pumps and fans). Existing experiences show that, in contrast to other thermal power plants, the auxiliary power demand in geothermal binary power plants can significantly vary depending on site-specific conditions.

The power demand for the geothermal fluid production, for example, is determined by the reservoir characteristics and the delivered flow rate, e.g. Heidinger, Sanyal, Legarth. When dimensioning the geothermal fluid flow from a specific reservoir, technical restrictions, such as the maximum installation depth and maximum pump capacity, must be considered.

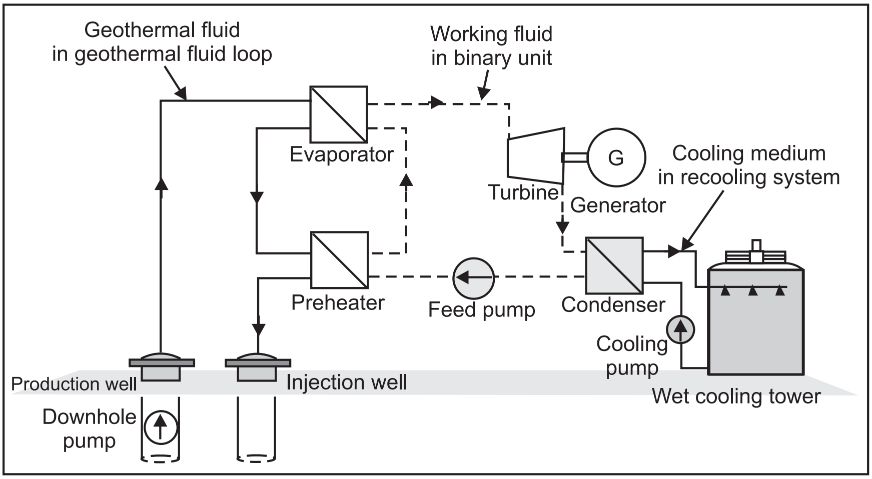



**Figure 14.2** Schematic setup of a geothermal binary power plant showing the different subsystems

Another important aspect is the over-proportional increase of the pumping effort with increasing fluid flow rate. Since a higher flow rate results in a larger draw down of the fluid level in the production well, the production effort shows a quadratic dependence with respect to the flow rate. The increase of the fluid production effort with increasing geothermal fluid flow rate is stronger for lower reservoir productivities (Fig. 14.3).

The auxiliary power consumed by the recooling system—which has a considerable influence on the net power output due to relatively large waste heat amounts—is significantly influenced by site preconditions and ambient conditions, e.g. Moya and DiPippo, Kröger, IPPC, Klenke. The relative amount of waste heat thereby increases with decreasing conversion efficiencies (Fig. 14.4). For removing the waste heat from the binary cycle, a suitable heat sink, such as surface water, water from groundwater wells or ambient air is necessary. In conventional power plant engineering, water cooling is usually preferred to air cooling due to the ability to realise lower condensing temperatures and therefore a larger power output. However, the precondition of sufficient supply of cooling water can at many sites, if any, only be met with additional technical and energetic effort. The design of the recooling system in geothermal binary power plants will therefore oftentimes be a compromise between technical realisation and energetic aspects.

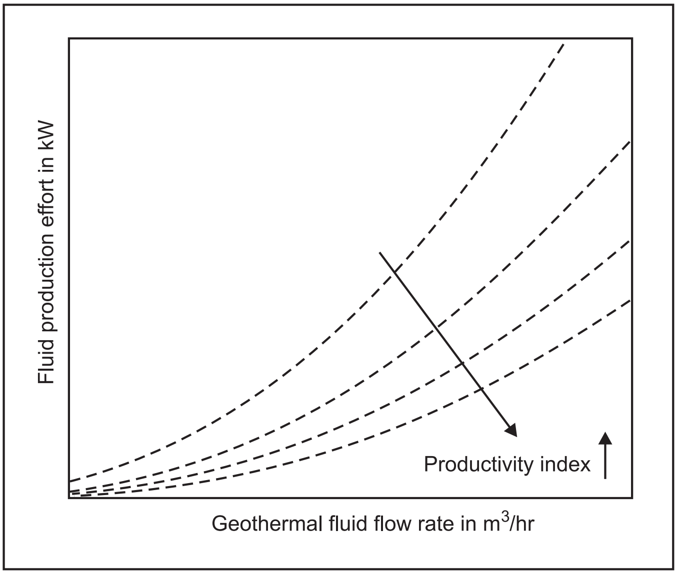



**Figure 14.3** Example of fluid production effort as a function of geothermal fluid flow for different reservoir productivities

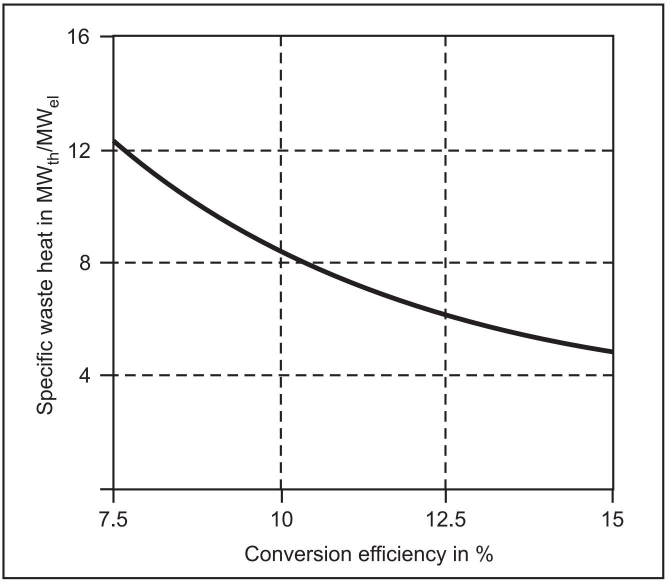



**Figure 14.4** Specific waste heat as a function of the conversion efficiency

Based on the considerations above, geothermal binary power plant design must focus on net electricity provision and integrate site-specific reservoir characteristics, ambient conditions and operation characteristics in a holistic design approach. In the following, such an approach will be introduced and applied in a theoretical case study.

It will be shown that the presented methodology leads to geothermal binary power plants with a higher net electricity output based on existing and proven technology.

### 14.4.1 Holistic design approach—theoretical considerations

The design of the subsystems in geothermal binary power plants depends on different site-specific influences and parameters. In order to design reliable and efficient geothermal binary power plants it is therefore important to integrate these different characteristics in an overall or holistic design approach. The most important aspects or differences of a holistic design approach compared to the separate design of each subsystem are:

1. *An optimum geothermal fluid flow rate:* The gross power which can be generated from a geothermal resource linearly increases with increasing geothermal fluid flow rate. However, the considerations above have shown that increasing the flow rate at a site also results in an over-proportional increase in power consumption of the fluid production system (Fig. 14.3). This means that an optimum geothermal fluid flow rate exists for which the net power provision of a geothermal binary power plant reaches its maximum. Assuming a specific plant setup on the surface, the optimum flow rate for a site with lower reservoir productivity is therefore lower. Referring to different surface plants setups, the optimum flow rate is increasing with a more efficient and better utilisation of the geothermal heat such as with more efficient (and reliable) binary units or the supply of the residual heat in the geothermal fluid after the heat transfer to the binary unit.
2. *An optimum working fluid:* The selection of the working fluid enables the adaptation of the binary conversion cycle to the characteristics of the geothermal heat source. This is due to different shapes of the dew-point curve and different evaporation characteristics which can be realised with different media and mixtures. The choice of a suitable working fluid is therefore an important aspect in designing geothermal binary power plants. A suitable working fluid must allow reliable operation (e.g. thermally stable in the long-term, compatible with other materials used in the binary cycle), a high conversion efficiency and a good utilisation (i.e. the cooling of the geothermal

fluid) of the geothermal heat. Due to the relatively large waste heat amount in geothermal binary power plants, also a selection of the working fluid according to the heat sink and operation characteristics must be considered.

3. *An optimum evaporation temperature:* The evaporation temperature contrarily influences the conversion cycle efficiency and the utilisation of the geothermal heat. Hence, an optimum evaporation temperature exists for which the power output reaches a maximum. Regarding the design of the evaporation also annually varying ambient conditions which might influence the condensation temperature must be considered. If a geothermal binary power plant should also supply heat in serial connection to the binary power unit, the evaporation temperature also depends on the temperature which is required at the outlet of the binary unit in order to provide a certain supply temperature. The outlet temperature of the geothermal fluid can be increased with higher evaporation temperatures. Another possibility is internal heat recuperation in case a dry working fluid is used.
4. *An optimum condensation temperature:* The gross power output of a binary unit is increasing for decreasing condensation temperatures due to the increasing enthalpy difference in the expansion machine. However, also the requirements for the recooling are increasing with decreasing condensation temperatures. This is because lower temperatures must either be realised by lower cooling sink temperatures such as in case of once-through cooling systems. At many sites, where once-through cooling is not an option, lower condensation temperatures can only be realised by a larger auxiliary power input to the fans of wet cooling towers or air coolers. The correlation between condensation temperature and auxiliary power demand is determined by the recooling system, its performance and the ambient conditions. Therefore, regarding the net electricity production, also an optimum condensation temperature does exist. It must be considered that the ambient conditions can significantly vary during the year. Regarding the relatively large waste heat amounts in geothermal binary power plants, the technical use of the waste heat (e.g. conventional cogeneration) can also reduce the demand for recooling.

## 14.5 Conversion technologies

A conversion technology represents the entire process of turning hydrothermal resources into electricity. Of the four available to developers, one of the fastest growing is the binary cycle, which includes a Rankine cycle engine.

### 14.5.1 Steam

'Dry steam' plants have been operating for over 100 years—longer than any other geothermal conversion technology, though these reservoirs are rare. In a dry steam plant like those at The Geysers in California, steam produced directly from the geothermal reservoir runs the turbines that power the generator. Dry steam systems are relatively simple, requiring only steam and condensate injection piping and minimal steam cleaning devices. A dry steam system requires a rock catcher to remove large solids, a centrifugal separator to remove condensate and small solid particulates, condensate drains along the pipeline, and a final scrubber to remove small particulates and dissolved solids. Today, steam plants make up a little less than 40 per cent of US geothermal electricity production, all located at The Geysers in California. Figure 14.5 shows a dry steam plant.

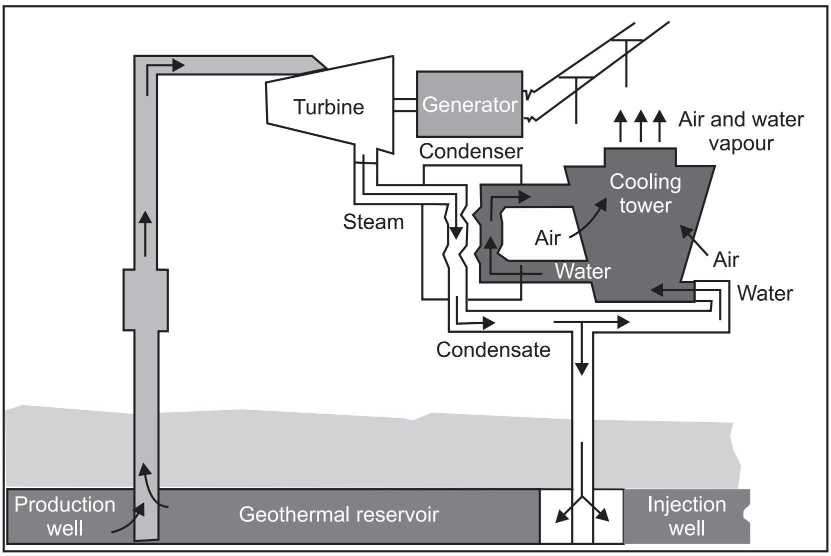



**Figure 14.5** Dry steam plant

### 14.5.2 Flash

The most common type of power plant to date is a flash power plant, where a mixture of liquid water and steam is produced from the wells. At a flash facility, hot liquid water from deep in the earth is under pressure and thus kept from boiling. As this hot water moves from deeper in the earth to shallower levels, it quickly loses pressure, boils and 'flashes' to steam. The steam is separated from the liquid in a surface vessel (steam separator) and is used to turn the turbine, and the turbine powers a generator. Flash power plants typically require resource temperatures in the range of 350–500°F (177° to 260°C). A number of technology options can be used with a flash system. Double flashing, the most popular of these, is more expensive than a single flash, and could concentrate chemical components if they exist in the geothermal water. Even considering potential drawbacks, most geothermal developers agree that double flash is more effective than single flash because a larger portion of the resource is used. Steam processing is an integral part of the gathering system for flash and steam plants. In both cases, separators are used to isolate and purify geothermal steam before it flows to the turbine. A flash system requires three or more stages of separation, including a primary flash separator that isolates steam from geothermal liquid, drip pots along the steam line, and a final polishing separator/scrubber. A steam wash process is often employed to further enhance steam purity. All geothermal power plants require piping systems to transport water or steam to complete the cycle of power generation and injection. Figures 14.6 and 14.7 show schematics of single and double flash-type power plants.

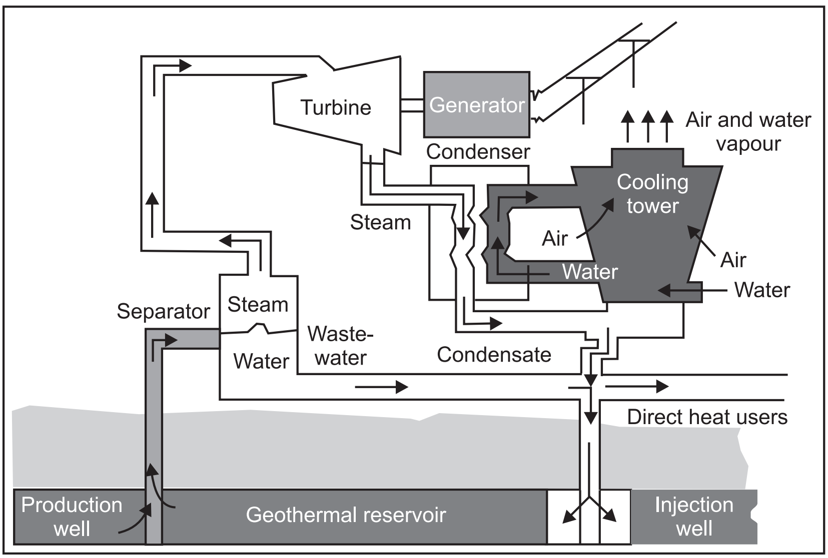



**Figure 14.6** Single flash steam power plant schematic

## 14.5.3 Binary

Technology developments during the 1980s have advanced lower temperature geothermal electricity production. These plants, known as ‘binary’ geothermal plants, today make use of resource temperatures as low as 165°F or 74°C (assuming certain parameters are in place) and as high as 350°F (177°C). Approximately 15 per cent of all geothermal power plants utilise binary conversion technology. In the binary process, the geothermal fluid, which can be either hot water, steam or a mixture of the two, heats another liquid such as isopentane or isobutane (known as the 'working fluid'), that boils at a lower temperature than water. The two liquids are kept completely separate through the use of a heat exchanger used to transfer heat energy from the geothermal water to the working fluid. When heated, the working fluid vapourises into gas and (like steam) the force of the expanding gas turns the turbines that power the generators.

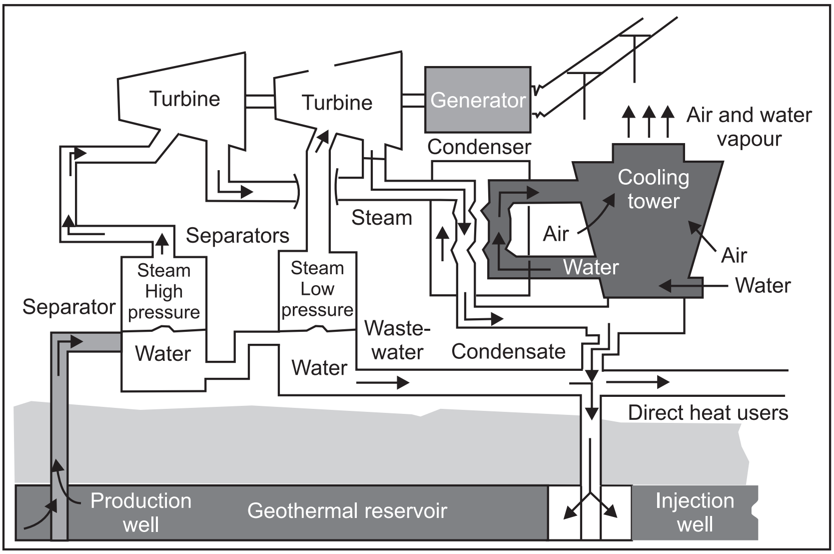



**Figure 14.7** Double flash steam power plant schematic

Geothermal fluids never make contact with the atmosphere before they are pumped back into the underground geothermal reservoir. Because the geothermal water never flashes in air-cooled binary plants, 100 per cent can be injected back into the system through a closed loop. This serves the dual purpose of reducing already low emissions to near zero, and also maintaining reservoir pressure, thereby extending project lifetime. For lower pressure steam, a two phase binary cycle is sometimes used. Two-phase systems are similar to traditional binary cycles, except the steam flow enters the vapouriser/heat-exchanger, while the geothermal liquid is used to preheat the organic motive fluid. The steam condensate either flows into the preheater or is combined in the geothermal liquid after the pre-heater. Since the steam pressure in the vapouriser/heat-exchanger remains above atmospheric pressure, the non-condensable gases (NCG) can be reinjected together with cooled-geothermal fluid or simply vented without the need for a power consuming vacuum pump (Fig. 14.8).

## *Rankine cycle*

A Rankine cycle, the commercial binary cycle in the United States, converts heat into electricity. Rankine cycles require an organic-based working fluid with a lower boiling point than water, and are thus often used with lower temperature geothermal resources. The four major pieces of the Rankine cycle include the boiler, turbine, cooling tower, and feed pump. The working fluid in a Rankine cycle follows a closed loop and is reused constantly (Fig. 14.9).

The Rankine cycle, which includes four processes that change the state of the working fluid, has been running geothermal power plants with success for over 100 years.

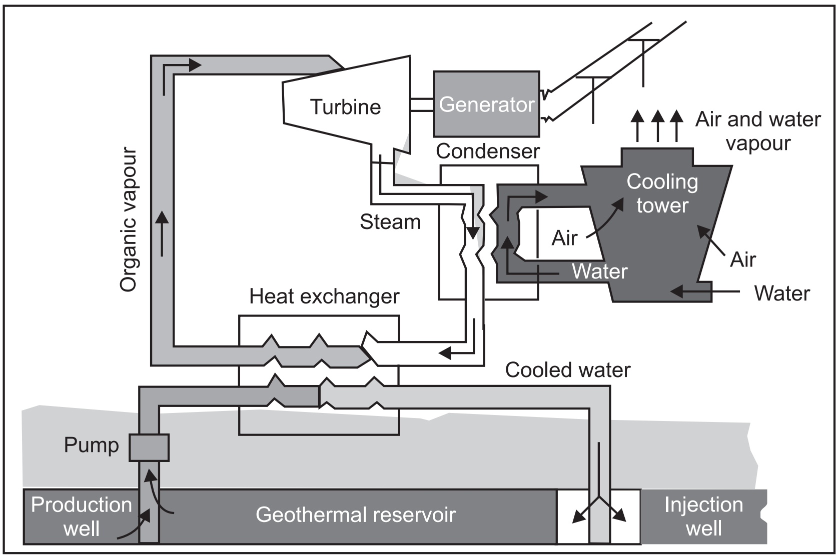



**Figure 14.8** Binary power plant schematic

## *Outlook for binary systems*

The ability to use lower temperature resources increases the number and type of geothermal reservoirs suitable for power production. According to some experts, lower temperature resources suitable for binary cycles will be the most common of all future hydrothermal resources developed. As binary use has increased, associated power technology has continued to improve. For example, advances in production pumps have allowed for sustained pump run time for years rather than months. Also, binary systems can now operate at lower temperatures than scientists previously thought possible. Improvements will likely continue as conventional energy prices increase. The post-2001 hike in energy prices has led to the replacement and/or expansion of older geothermal generation systems using newer technology, particularly incrementally improved binary technology. In addition, several geothermal resources discovered in the 1980s are today undergoing their first commercial binary development. These new developments, while substantial, represent only a small fraction of the potential for new generation using binary technology that is being promoted by developers throughout the country.

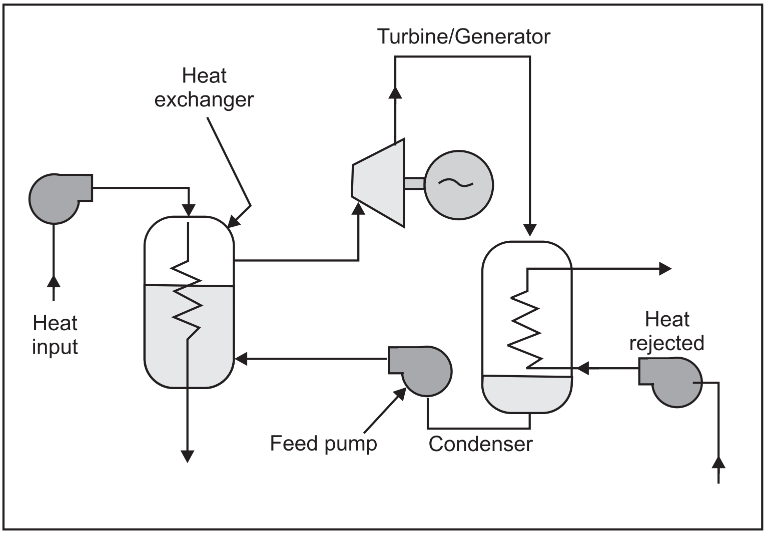



**Figure 14.9** Rankine cycle schematic

### 14.5.4 Flash Binary Combined Cycle

A combination of flash and binary technology, known as the flash/binary combined cycle, has been used effectively to take advantage of the benefits of both technologies. In this type of plant, the flashed steam is first converted to electricity with a steam turbine, and the low-pressure steam exiting the back-pressure turbine is condensed in a binary system. This allows for the effective use of air cooling towers with flash applications and takes advantage of the binary process. The flash/binary system has a higher efficiency where the well-fields produce high pressure steam. This type of system has been operating in Hawaii since 1991 at the Puna Geo Venture facility.

For a high enthalpy water-dominated resource, the most effective power plant configuration may be integration of a combined cycle for the steam and a standard binary unit for the separated brine into one unified plant. In this case, each unit operates with common controls, fluid collection, and reinjection systems. The developer must closely monitor the injection water temperature in combined cycle systems, as declines could occur that lead to scaling. As with any geothermal conversion technology, proper management is critical.

### 14.5.5 Choosing a conversion technology

Resource characteristics—temperature, pressure, volumes of fluid produced, and chemical properties of the geothermal reservoir—are the primary determinants of the size and type of power conversion equipment. Assuming sufficient volumes of fluid are produced, temperature determines the most efficient conversion design.

While binary plants can utilise any temperature resource, low temperature resources are constrained to the binary model. Medium temperature resources can be economical by using either flash or binary systems. High temperature resources are most economical when steam or flash systems are employed, as these are simpler and therefore less costly. Flash systems are less expensive than binary systems, but may not be as efficient at lower temperatures.

Steam plant equipment costs rise as temperature decreases (as a result of efficiency losses). Despite a more complex design, binary power systems are generally less expensive than steam systems for temperature close to 350°F. The cost of binary systems rises as temperature drops. Binary systems may be preferred in highly sensitive environmental areas, since they operate as closed-loop, virtually emissions-free systems.

## 14.6 Cooling types

A cooling system, which condenses the working fluid, is essential for the operation of any modern geothermal power plant. A cooling tower provides a greater temperature and pressure differential across the turbine to increase efficiency. The larger this differential, the greater the driving force across the turbine, and the greater the efficiency. Since the earliest days of the industrial revolution, improving the condensing (cooling) process has been a prime concern of scientists and engineers. Advances during the past few years have improved the cooling process. For example, high efficiency fills offer low-cost, compact towers that enhance air-to-water contact. New fills can improve the flow of the geothermal resource, reduce clogging, and assist with cleaning insoluble materials. The use of fibreglass structures rather than wood for cooling towers can improve both cost and fire resistance.

Developers have two basic cooling options: water or air cooling. Hybrid air-water cooled systems have been demonstrated to a limited extent and are considered important for future advancement. Both air and water-cooled systems use cooling fan motors. Some maintenance is required, typically an annual check-up of fan motors and belts as well as system lubrication.

### 14.6.1 Water cooled

Most power plants, including most geothermal plants, use water-cooled systems—typically in cooling towers. As these are more efficient, they generally require less land than air-cooled systems. Water-cooled systems are less expensive to build and operate if water is readily available and inexpensive to obtain. These systems lose most of the water to the atmosphere by evaporation in the form of water vapour, while the remainder is injected back into the system. Emissions from a wet cooling tower (i.e. water vapour plus dissolved solids or minerals) depend upon the quality of the geothermal liquid injected back through the system.

While today water cooling is mostly used in higher-temperature non-binary facilities due to the use of the geothermal fluid for cooling, a few existing and developing binary facilities in the US utilise water-cooled systems. The binary plants at Heber, East Mesa and Wendel-Amedee, all in California, use water cooling. The Raft River geothermal plant, the first in Idaho, is a binary facility that uses water cooling.

### 14.6.2 Air cooled

Because the efficiency of power generation is affected by the difference between the temperature of the fluid exiting the turbine and the temperature of the cooling medium, air-cooled systems are influenced by seasonal changes in air temperature. These systems can be extremely efficient in the winter months, but are less efficient in hotter seasons when the contrast between the air and water temperature is reduced. Plant efficiency typically increases by 15 per cent during colder months and decreases by 15 per cent during warmer months. This means that an air-cooled plant is least efficient during summer peak energy demand, which typically takes place during the hottest hours of the day due to air conditioning. The ideal temperature difference between the air and the resource is 200°F (93°C) for an air-cooled system.

Air cooling is beneficial in areas where extremely low emissions are desired, where water resources are limited or where the view of the landscape is particularly sensitive to the effects of vapour plumes (as vapour plumes are only emitted into the air by water cooling towers). While air-cooled systems are only used at binary facilities today, these could theoretically be used with any geothermal conversion technology (Fig. 14.10).

### 14.6.3 Choosing the right cooling system for a site

Climate and altitude can impact cooling technology. Water cooling is very efficient in hot dry climates; air cooling is most efficient in cool climates; and in hot humid climates where efficiency for both technologies is reduced, either may be applied. Other factors to consider include water and land availability, value of power during hot months, aesthetics, and environmental issues.

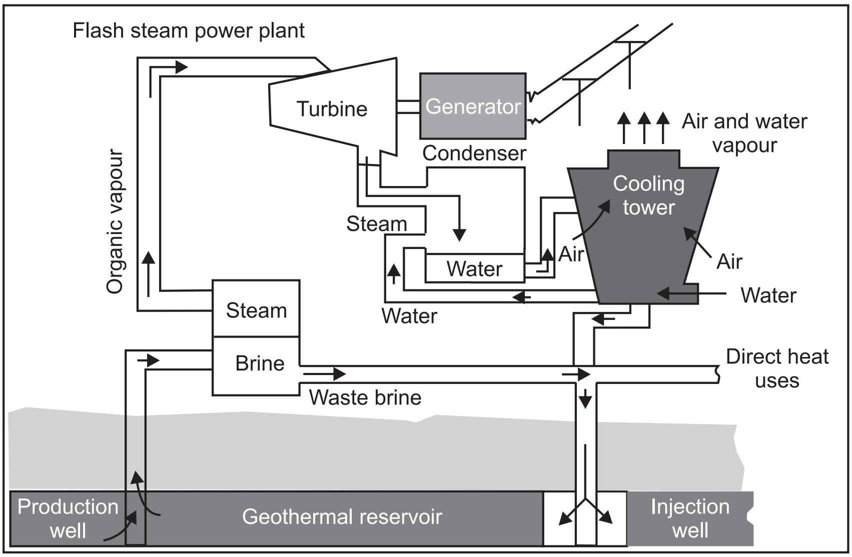



**Figure 14.10** Diagram of geothermal power plant with water-cooled system

Because water-cooled systems require biotic and sometimes chemical water treatment to prevent algae blooms or mineral deposition, some developers claim that operation costs of air-cooled systems are lower than those of water-cooled systems. However, the upfront cost of an air-cooled system is higher per kilowatt than a water-cooled system. As is typically the case, a developer must consider upfront versus lifetime costs.

## 14.7 Structuring power plant to minimise impact

While a geothermal power plant's impact is relatively small compared to that of a fossil fuel plant, geothermal operators still take steps to mitigate any negative affects caused by development.

### 14.7.1 Noise

A variety of noise muffling techniques and equipment are available for geothermal facilities. During drilling, temporary noise shields can be constructed around portions of drilling rigs. Noise controls can be used on standard construction equipment, impact tools can be shielded, and exhaust muffling equipment can be installed where appropriate. Turbine-generator buildings, designed to accommodate cold temperatures, are typically well-insulated acoustically and thermally, and equipped with noise absorptive interior walls.

### 14.7.2 Visual impacts

Visual impacts related to geothermal development include night lighting on the power plant, visibility of the transmission line, and the presence of plumes at facilities using water-cooled systems. Fossil fired power plants have all of these visual effects and more. Detailed site planning, facility design, materials selection, landscaping programs, and adjustment to transmission line routing are key aspects of geothermal operations that can reduce impacts. Developers may paint their power facility forest green to blend in with the surrounding landscape.

Additionally, some companies use non-specular conductors, which reduce reflection and glare on transmission lines. Other visual impacts, such as construction equipment, are only of concern on a temporary basis. Construction vehicles, drill rigs, and other heavy equipment impact the visual quality of an area for a limited amount of time.

### 14.7.3 Mitigation to reduce impact on wildlife and vegetation

Geothermal plants are designed to minimise the potential effect on wildlife and vegetation. Pipes are insulated, which prevents thermal losses and protects animals from burns if they contact the pipes. Spill containment systems are constructed, and areas with sensitive biological or cultural/archeological resources and threatened or endangered species are avoided. Pipelines are built high or low to help minimise impacts to wildlife movement. Geothermal plants do not cause additional disruption from offsite drilling, the construction of pipelines over long distances (as is typically necessary for natural gas transportation), and mining and transportation of coal and uranium ores.

### 14.7.4 Monitoring activities

Monitoring is a key component of geothermal maintenance and mitigation. Ongoing monitoring activities could include but are not limited to well pressure, water chemistry, surface site, subsidence, biological resources, and deep temperature monitoring. Most mitigation measures are set forth in permitting conditions and environmental documents available for public review.

### 14.7.5 Maintenance

Geothermal plants are designed to fit the resource of the plant site. Reservoir chemistry can vary dramatically from one resource to another. California's Salton Sea area, for example, has some of the most mineral-rich geothermal water anywhere in the world. This can create challenges caused by corrosion and scaling. The facility at Mammoth Lakes, with a resource comparatively lower in mineral concentration, requires less maintenance.

On average, geothermal plants are available for power generation 97 per cent of the time. Plants are typically off-line near 3 per cent of the time due to routine scheduled maintenance as part of the power cycle management process. By proactively inspecting parts, wear and tear-associated problems are kept to a minimum.

Like any facility, a geothermal plant can be impacted by fire, lightning, a wind storm or other natural disasters. Geothermal developers are prepared for such unlikely occurrences, both in their mitigation and their maintenance techniques. Stop-gap emergency measures are typically put in place.

## 14.8 Efficiency

Efficiency is broadly defined as the ratio of the output to the input of any system. All thermal power plants have a fraction of 'waste heat'. While efficiency is an important measure of power generating facility performance, comparing efficiency values for geothermal and other renewable technologies, as well as for fossil fuels, poses significant challenges.

The public interest in energy efficiency arose as a fossil fuel issue: that is, the less fuel used per output, the fewer emissions and the greater quantity of depleting fuels conserved. Burning fossil fuels to generate electricity contributes to climate change, health problems, and ecosystem damage. As fossil fuel resources become scarcer, costs skyrocket. That's why efficiency—maximising the energy output from a quantity of burned fossil fuel—is so important for traditional power plants.

The American Council for an Energy Efficient Economy (ACEEE) has pursued increased coal plant efficiency as a means for reducing emissions. According to ACEEE, coal plants grandfathered by the clean air act 'emit 3–5 times as much pollution per unit of power generated as newer, coal-fired power plants and 15–50 times as much nitrogen oxides and particulates as new combined-cycle natural gas power plants'. Older and less efficient plants have 15 per cent higher average heat rates per unit of generation than modern combined-cycle plants, according to ACEEE.

For renewable energy use, in contrast to fossil fuel use, efficiency is primarily an economic concern. Maximising the output per input of available energy is still important, but the public issues are confined primarily to land use, not climate change, health and conservation issues. Unlike geothermal and other renewables, fossil fuel use is not sustainable even if managed properly and used efficiently.

At a geothermal facility, the fuel source is not burned. That means air emissions are substantially lower than at a fossil fuel facility. Because the geothermal resource—the fuel source—doesn't have to be shipped from far-off locations, there is no environmental impact related to transportation as with traditional resources. The geothermal resource is continuously available and highly reliable. Geothermal power plants regularly inject geothermal liquids back through the reservoir, thereby improving the lifetime of the plants. While both conventional plants and geothermal plants must reject heat to the surroundings—a consequence of the Second Law of thermodynamics, discussed in further detail below—geothermal plants result in more heat rejection per unit of useful power output than conventional plants.

Besides more obvious distinctions related to emissions and sustainability, other technology and resource differences must be considered when comparing efficiencies. Resource temperature is one important factor. At fossil fuel facilities, resources can reach temperatures of 1000°F (538°C) or higher. At geothermal power plants, in contrast, temperatures are lower because resources are heated naturally, within their natural confines, rather than through external heating. Because efficiency decreases with lower temperature resources, the quantity of heat input required to produce a given megawatt output increases, and so too does the percentage of that input that must be rejected as waste heat. In geothermal plants, in contrast to fossil fuel plants, more of the energy resource is needed to produce the same output of electricity. That's because more low 'quality' energy sources (e.g. resources at lower temperatures) are needed to produce the same electrical output, and geothermal resource temperatures are lower than coal temperatures.

The geothermal industry has, over the years, worked to define geothermal efficiency in a way that can be easily understood by the general public and compared across technologies, while accurately and fairly characterising the renewable energy resource. The issue is further complicated because experts use a variety of efficiency categorisations, depending upon the context in which an efficiency measurement is needed and the characteristics of the resource and plant. Some of these efficiency measurements cannot be equitably compared. What follows is a selection of some of the ways in which geothermal efficiency can be described. Rather than choosing any one efficiency description over another, this section seeks to identify several of the most popular ways of assessing geothermal efficiency.

### 14.8.1 First Law of Thermodynamics

The First Law of Thermodynamics states that energy cannot be created or destroyed; it can only be converted from one form to another. The First Law is used to categorise 'the performance of cyclic conversion systems like fossil-fired, steam power cycles or geothermal cycles. This efficiency is a measure of the portion of heat added to a power cycle that is converted to work, i.e. the ratio of network produced to the heat added to the cycle.' The first law is a conservation law (Law of Conservation of Energy). Regarding geothermal power plants, 'the 1st Law requires that any electricity that is generated (energy out) must balance with the energy extracted from the geothermal resource ± any other energy uses and losses to the environment'.

The First Law does not distinguish between the potential type and quality of energy that is received or delivered by a plant. This means that high quality, concentrated energy that can be used to produce electricity is not valued any more than dispersed, low-grade heat energy incapable of producing electricity.

### 14.8.2 Second Law of Thermodynamics

The Second Law provides direction to the First Law: while energy can neither be created nor destroyed (First Law), important limitations exist in the capacity of energy to do useful work. The Second Law states, in simple, generalised terms, that heat can never be converted completely into work, because some of the energy must flow from high temperatures to a low temperature sink. This means that 100 per cent efficiency is impossible. Second Law efficiency is defined as the ratio of the network to the available energy. Available energy, also referred to as exergy or availability, is the amount of work that can be completed using ideal thermodynamic processes to bring a fluid into equilibrium with a heat reservoir. 'It differs from energy in that it is consumed or dissipated during processes that change a fluid's entropy', or measure of disorder of a system. These processes include heat transfer processes, pressure rises in pumps, compressors and fans, expansions in turbines, pressure drops in piping, etc. The Second Law efficiency measures how 'efficiently the power cycle converts available energy into work'. Second Law efficiencies depend upon a number of factors, including the sink temperature of the power plant. The larger the temperature difference between the heating source and cooling sink, the more efficient a plant will be, assuming all other factors are the same. Plant developers may purposely limit the temperature of the geothermal fluid leaving the plant to prevent mineral precipitation (primarily silica). 'When this temperature limit is imposed, some define Second Law efficiency based on a modified available energy term that uses the minimum temperature instead of the ambient or sink temperature as the reference condition. Second Law efficiencies defined in this manner will be higher in magnitude.'

### 14.8.3 Comparing First and Second Law efficiencies

Second law efficiencies are generally, but not always, higher than first law because the available energy term (used in Second Law efficiency calculations) tends to be less than the quantity of heat removed from the geothermal fluid (First Law). Other, more subtle differences can sometimes mean that a plant at which Second Law efficiency is made higher through improvements or adjustments will actually result in a lower First Law efficiency.

### 14.8.4 Carnot efficiency

Carnot efficiency is often used to discuss geothermal power plants and heat engines in general. Binary plants, unique among geothermal conversion types, exist in closed power cycles. As such, power cycle definitions are often considered the most appropriate mechanism through which to categorise binary efficiency.

#### *Carnot cycle*

An ideal, frictionless engine in a closed power cycle is known as a Carnot cycle. A Carnot cycle involves four processes and represents the maximum First Law efficiency possible in a specified system. A Carnot Engine is reversible and runs in a cycle, with all of its heat exchanges taking place at a source temperature and a sink temperature. A working engine operating between two heat temperature limits can never exceed Carnot efficiency. Even an ideal, frictionless engine can't convert 100 per cent of its input heat into work.

Some geothermal experts prefer to use other vehicles to set the thermodynamic limit on cycle efficiency for geothermal binary plants. The main reason for this is that geothermal is a variable temperature process—a geothermal liquid enters a plant at a high temperature and cools off as it moves through the plant—while Carnot assumes a heat source operates at a constant temperature.

### *Triangular cycle*

One expert has suggested that the Triangular cycle is the more appropriate ideal cycle upon which to base the maximum binary efficiency. A Triangular cycle recognises that a heating source cools rather than remains at a constant temperature as it transfers heat. An ideal Triangular cycle will more closely mirror a working binary plant without imposing Carnot's 'unreasonably high bar'. Carnot and Triangular cycles are identical in the first two processes. However, the Triangular cycle adjusts for temperature differences in the last half of the cycle: ideal Carnot efficiency assesses the difference between the heat source and heat sink as a fraction of the heat source; ideal Triangular efficiency assesses that same difference (i.e. heat sink subtracted from heat source) as a fraction of the heat source considered along with the heat sink. The distinction is more succinctly represented in the equations below:

Ideal carnot efficiency: $(T_H - T_L)/(T_H)$

Ideal triangular efficiency: $(T_H - T_L)/(T_H + T_L)$

where, $T_H$ = absolute temperature of the heat source and $T_L$ = absolute temperature of the heat sink.

Ideal triangular cycle efficiencies will always be lower than ideal Carnot cycle efficiencies for the same temperature limits.

## 14.8.5 Efficiency using power and flow measurements

One way to measure efficiency without using the First or Second Law is through power and flow measurements. Such measurements can be classified as either specific power output (SPO) or specific geofluid consumption (SGC). SPO, which can be used for any type of geothermal power system, considers the amount of net power produced per unit flow of geothermal fluid. For given resource conditions, the higher the SPO—typically measured in watt hours per pound or kilogram of geothermal fluid—the more efficient a plant is. The geofluid flow rate needed to produce a certain net power is termed the SGC, which is the inverse of the SPO. SGC measures the flow rate per unit power produced. Some experts consider this the simplest and most effective measurement of efficiency. Dividing the SPO by the available energy is one way to measure the Second Law efficiency.

### 14.8.6 Turbine efficiency

Rather than considering the efficiency of the entire conversion system, another method for rating geothermal efficiency is to consider certain power plant components. The turbine, for example, provides a useful measurement.

A turbine is a steam-powered machine that causes a shaft—a rotating rod that transmits power or motion from the turbine—to produce electricity through movement. Improvements in turbine design in the past several years have increased geothermal turbine efficiency to over 85 per cent.

### 14.8.7 Gross versus net efficiency

When parasitic load is reduced at a facility, a plant will operate more efficiently. Gross plant efficiency includes the parasitic load in its assessment, while net plant efficiency only considers the electricity that can produce power (total power minus parasitic load). As a result, gross plant efficiency will always be higher than net efficiency.

### 14.8.8 Assessing efficiency measurements

While efficiency is important, it is only one characteristic among many that must be considered when choosing the most appropriate energy option for a particular location. Other factors, such as reliability, cost, environmental impact, and sustainability must also be considered. A significant 'energy cost', is associated with producing and transporting fossil fuel for use at a power plant, while the associated costs at a geothermal facility are minimal.

When efficiency assessments must be made, a single number will be meaningless unless the calculations and assumptions used to arrive at that number are made transparent. For example, if a fossil fuel power plant developer cites its 'efficiency' as 40 per cent, and a geothermal developer cites a similar number, these two plants do not necessarily have the same efficiency. To begin to assess efficiency values, an inquiry must be made into any calculations used. In many cases, two efficiency numbers should not even be compared because they measure two different types of efficiencies.

As has been shown, efficiency can be represented in a variety of ways, all of which can be useful and accurate depending upon the situation and the needs of the developer. The point is not to choose one method of calculating efficiency over another. Rather, it is to consider efficiency as one of many factors that can influence power plant development preferences; and then to show which efficiency method is chosen, which calculations and adjustments are made, and why.

## 14.9 Non-traditional geothermal systems

Most of today's geothermal electricity comes from traditional geothermal conversion technology that integrates no other types of resources into the system. While a significant undeveloped hydrothermal resource base is available, several other technology applications have been considered, or are emerging, that could further expand geothermal potential. Still other applications have already been successfully demonstrated and used commercially. What follows is a rundown of some of these applications, with particular focus upon power plant infrastructure.

### 14.9.1 Geothermal Hybrid Systems

Hybrid systems, which pair a geothermal hydrothermal resource with another type of resource, offer the flexibility of determining the optimal steam temperature independent of the geothermal source temperature. This adds increased reliability to the system design.

Hybrid systems can increase efficiency, and therefore create more electricity without expanding the use of the geothermal resource. In Fig. 14.11, the energy source for the first two heat exchangers is geothermal; the energy source for the third (labelled 'superheater'), could come from any other source, including biomass, coal or hydropower.

#### *Biomass*

Geothermal can be used in conjunction with biomass. The company Infinifuel Biodiesel, for example, has constructed a biodiesel processing facility at a small Nevada geothermal power plant in Wabuska. At this facility, camelina oil seed algae is transformed into diesel fuel. The facility is almost entirely self-contained, largely due to heat supplied by a geothermal plant. The plant works by growing algae, crushing or pressing these materials into vegetable oil and biomass, adding the biomass to alcohol, and finally mixing the biomass/alcohol combination with vegetable oil and heated it using geothermal power for the biodiesel plant. This geothermal facility, which uses 220°F (104°C) water, produces enough power to run the Wabuska facility and sell additional power. Infinifuel plans to expand to other locations in Nevada and beyond.

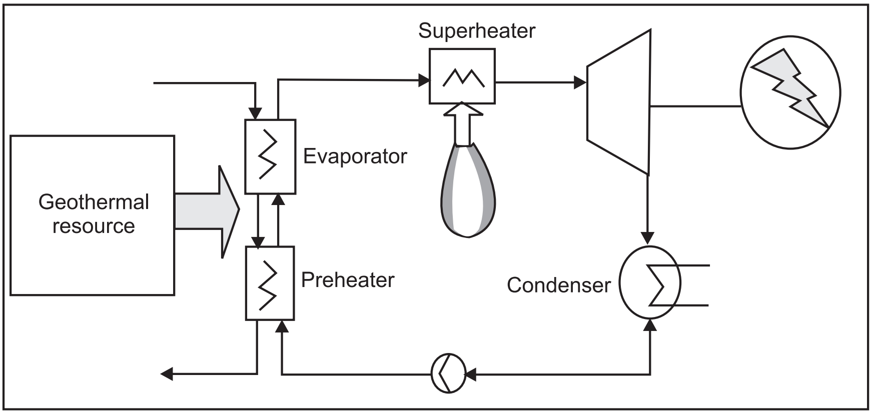



**Figure 14.11** Geothermal hybrid power plant system

## *Combined heat and power*

At certain resource locations and under favourable circumstances, geothermal resources can be used both to produce electricity and also for direct use purposes. This hybrid model is known as 'combined heat and power' or CHP. CHP increases net efficiency, improves power plant economics, and creates jobs. CHP essentially takes the 'waste' heat produced by geothermal electric plants and uses it for other useful purposes. Cascading water from a geothermal power plant provides energy for direct use projects such as district heating (and possibly cooling), greenhouse and fish pond heating, industrial applications, and spa and pool heating. CHP has been used on a commercial basis at several sites around the country. Figure 14.12 shows a diagram of a combined heat and power geothermal facility.

Another example of the combined use of geothermal electricity and direct-use heating is highlighted in one of Iceland's top tourist attractions, the blue lagoon. At this location, geothermal water from a working geothermal power plant is piped directly to a large body of water, the blue lagoon. The water is said to offer healing properties due to its unique array of minerals, silica, and blue algae. While the blue lagoon is a great success in Iceland, similar applications have not been constructed at large-scale US power plants.

## *Solar*

The US Department of energy (DOE) has considered solar-geothermal hybrid electric power systems on and off for decades. In 1979, a hybrid concept was considered where wellhead fluid was pressurised, with solar heat added prior to flashing. Such a system was assumed to provide higher quality steam and thermodynamic advantage over a conventional geothermal flash system, but the introduction of hotter than usual geothermal liquid resulted in increased scaling and corrosion.

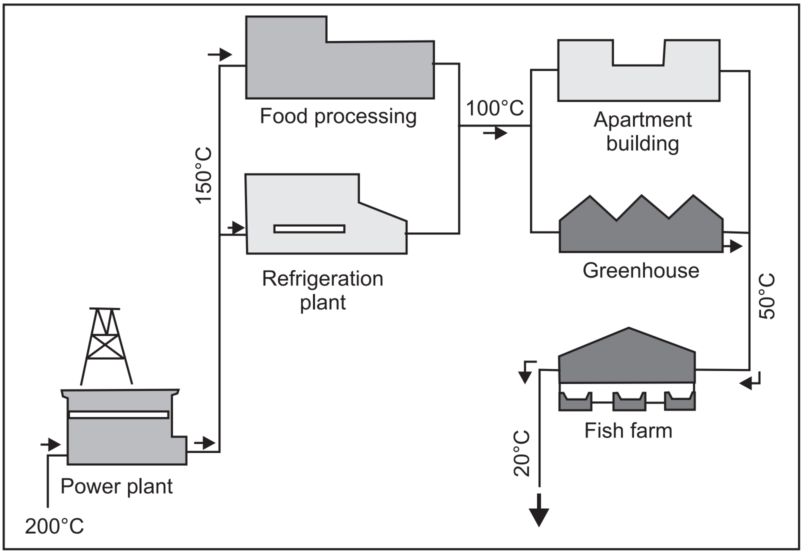



**Figure 14.12** Combined heat and power (CHP) diagram

The study conducted by the DOE in 1979 concluded that while geothermal-solar hybrid systems would be comparatively more efficient than stand-alone geothermal plants, hybrids would not offer economic advantages over stand-alone systems. This conclusion has been replicated in subsequent years. Solar-geothermal hybrids may, however, be more cost effective than stand-alone solar facilities. Figure 14.13 shows the solar-hybrid configuration.

Solar has also been proposed as a means to hedge risk associated with geothermal production. In such solar-geothermal hybrid scenarios, a geothermal power plant capacity is proposed that is higher than the 'proven capacity' derived from reservoir engineering assessments of the geothermal resource. A larger power plant size results in higher initial income but also a higher probability of more rapid resource depletion.

To offset the risk that, after 5–10 years of operation, resource depletion might impact generation, the power plant would be constructed so that its heat supply could be supplemented by solar, thereby maintaining generation.

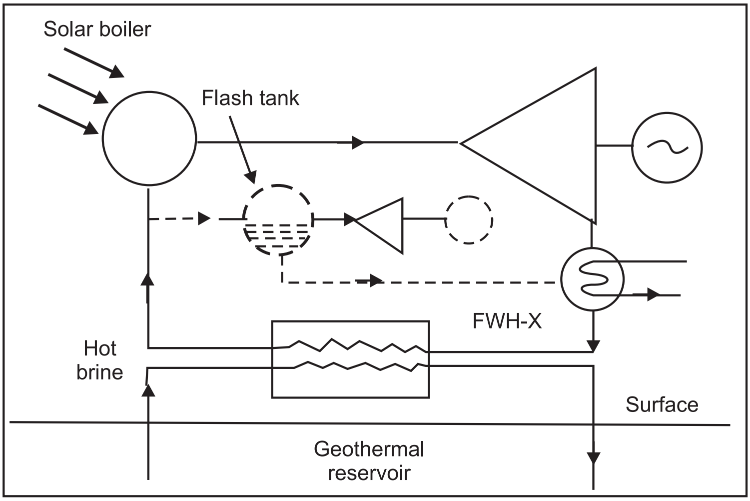



**Figure 14.13** Solar-geothermal hybrid facility

One new idea that has been proposed, though not commercially implemented, involves the use of solar and geothermal energy to recover oil from depleting oil and gas fields. Solar augmented geothermal energy (SAGE), according to an abstract presented at the University of Texas, converts depleting oil and gas fields and comparable reservoir strata to ‘synthetic geothermal’ reservoirs over wider regions. SAGE stores/banks solar energy, using naturally occurring geothermal liquids, for geothermal power generation, while enhancing oil recovery.

## *Hybrids with heat pumps*

A separate application of geothermal energy, geothermal heat pumps, can be used in combination with any other electricity source. Geothermal heat pumps make use of the natural heat trapped below the surface of the earth that averages 65°F (18°C). This heat provides cooling in the winter and warming in the summer. Unlike hydrothermal electricity production, direct use systems do not require a geothermal reservoir. Geothermal heat pumps function like traditional heat pumps: they can heat, cool, and, if so equipped, supply a house with hot water, yet they are significantly more efficient that traditional heat pumps, allowing the user to become less dependent upon the electric grid for heating and cooling. Though any electricity source can be used to power a geothermal heat pump, using renewable power makes the pump 100 per cent green. Figure 14.14 shows a hybrid cycle flow diagram.

### *Geopressured resources*

One particularly promising geothermal-fossil fuel hybrid is known as a ‘geopressured’ system. A geopressured geothermal facility operates on both natural gas and geothermal fuel. Geopressured geothermal resources have not been tapped since they were successfully demonstrated almost two decades ago, when oil and gas costs were low. Today’s increasing oil and gas costs make the economics of geopressured applications look particularly promising.

## 14.9.2 Enhanced Geothermal Systems (EGS)

Enhanced geothermal systems (EGS) have recently gained much attention as a promising application for geothermal energy. A Massachusetts Institute of Technology (MIT) report discusses possible modifications to the design of a power plant that captures resources through EGS technology. According to the report, EGS technology could be used through existing geothermal power systems, including binary, flash-binary combined cycle, double-flash plant or single flash plant (with several adjustments in power plant components).

EGS resources are similar to traditional hydrothermal resources, except they include one or all of the following: (i) a dense rock reservoir through which liquid cannot easily pass (one that lacks the usual needed porosity and permeability), (ii) insufficient quantities of steam and/or hot water and, (iii) deeper than usual drilling depths.

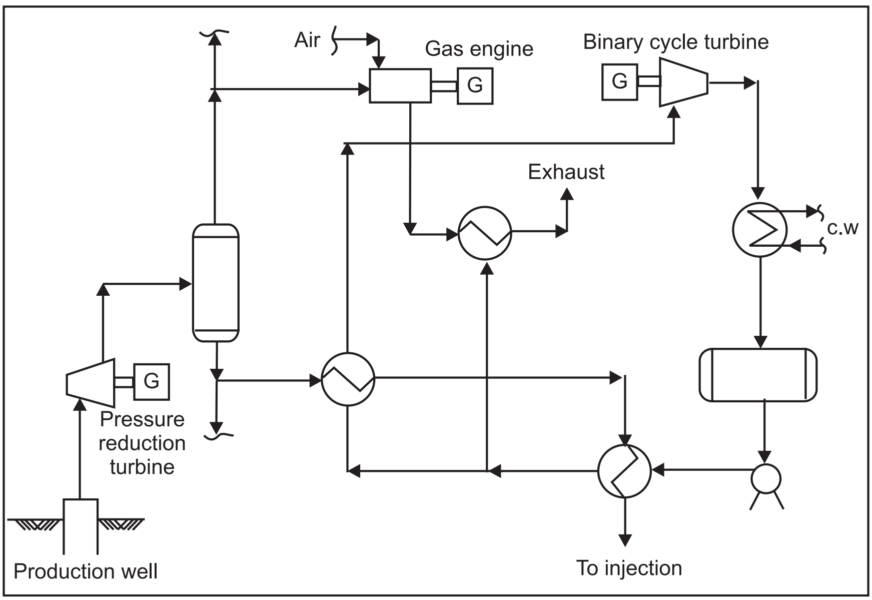



**Figure 14.14** Hybrid cycle flow diagram

Highest temperature resources, known as supercritical geothermal systems, would need so-called ‘triple-expansion systems’. These are variations on double-flash, with the addition of a ‘topping’ dense-fluid, back-pressure turbine. The turbine is designed to handle the very high pressures likely to be found with EGS geofluid. However, these systems would require great depths, deeper than 4.7 miles (7.5 km) except for very few areas in the United States. Thus standard EGS systems utilising binary or flash plants are more likely to be developed in the near term. Because EGS has not been successfully demonstrated to date, researchers can only postulate about the power plant that will be needed. However, certain aspects of EGS technology could impact power plant choice. These include:

1. Fluctuations in non-condensable gas content
2. Temperature variations of the heat source
3. Flow variations of the resource
4. Size of the power plant

### 14.9.3 Outlook for Non-Traditional Geothermal Power Systems

Some of the non-traditional systems discussed in this section, including EGS and oil and gas co-production, show great promise. Some have been demonstrated (geopressured) or even used commercially (CHP) but could be significantly expanded in the future. Still other non-traditional systems, such as solar-hybrids, are not as cost-effective as stand-alone geothermal systems, despite efficiency increases. The commercial and technological viability of each of these non-traditional systems requires not only research and development, but also demonstration projects. Geothermal investors are generally wary of incurring the extra risk associated with trying out a new system before any other developer, especially when the high upfront costs of traditional systems are taken into account. Many developers say they’ll be the first in line to construct the second model, but they can’t afford to take the risk to construct the first.

## 14.10 New technology

The value of new technological innovations varies from site to site. At The Geysers, for example, where non-condensable gases influence electricity output, a major improvement for the future could be to upgrade the gas removal equipment for added flexibility, thereby handling a wider range of non-condensable gas concentrations in the steam. At resource locations without non-condensable gases, such innovation would be of little value to developers. What follows is a sample of some promising new developments in geothermal surface technology. It is not an exhaustive list, nor is it an evaluation of which technology is better than another. Rather, this section offers a selection based on discussions with geothermal experts.

### 14.10.1 Near term versus long term

Incremental technology improvements—those that marginally increase the efficiency of a particular power plant component, for example—might prove most valuable in the near term. Geothermal power plants can always benefit from reduced parasitic load, reduced power expenditures related to cooling fans, improvements to the power substation, and other modest technological advances. Incremental improvements can be commercially implemented more quickly than larger, more revolutionary advances, and can be incorporated into existing designs with comparatively lower risk.

Major surface technology advances, in contrast, typically require considerable research, field experience, and technology trials, along with multiple field applications, before industry and investors are willing to incur the added risk associated with large-scale innovations. Major technology advances could be equally or even more valuable than incremental advances over the long-term, but the former will likely be implemented commercially only after years of research, development, and field experience.

### 14.10.2 Increasingly standardised, modular geothermal conversion systems

Modular energy conversion systems have already been engineered by existing geothermal companies. Even so, some experts believe modular systems continue to hold promise for further cost reductions. Modular components and subcomponents reduce costs because they can be pulled from off-the-shelf designs that are standardised and mass-produced. Once a plant site is established, a developer can move ahead more rapidly with plant development using modular systems. More costly custom-engineered modules tend therefore to be needed only on a limited basis. Modularity allows developers to more easily add capacity after a reservoir has been found to be capable of additional production.

Increasing modularity does not necessarily indicate small size. Modular units can be in the hundreds of kilowatts or the hundreds of megawatts. Smaller power plants may be more promising in non-traditional power applications, such as oilfield co-production, but larger plants will continue to play a role as new technologies such as EGS become commercially viable.

## 14.10.3 Mineral recovery

Further research and development could make the separation of minerals from geothermal water, known as mineral recovery, a viable technology. Some geothermal fluids contain significant concentrations of dissolved minerals, while others are virtually mineral free. Mineral recovery offers several benefits, which generally fall into categories of either improving the function of the power plant (reducing scaling, allowing greater power production by lowering the injection temperature) or increasing profits (through the sale of mineral by-products). Often a variety of benefits will result. Minerals found at geothermal power plants include zinc, silica, lithium, manganese, boron, lead, silver, antimony and strontium.

### *Silica recovery*

While silica can be a useful additive in products such as paint, paper, tyres, and toothpaste, it negatively impacts geothermal power plants by clogging pipes, wells, and heat exchangers. DOE has designated silica as one of the most promising minerals suitable for recovery due to its high commercial demand and its potentially negative impact on geothermal systems when not removed or reduced.

Lawrence Livermore National Laboratory (LLNL) has developed a technology for extracting silica from geothermal water. Silica extraction increases the efficiency of a geothermal power plant, provides a marketable silica by-product, and produces freshwater that can be used as a heat exchanger coolant. In the livermore extraction process, geothermal water is separated into freshwater and concentrated brine (heavily salted water) by a reverse-osmosis separation process.

The freshwater is used for evaporative cooling, and the concentrated brine is pumped into a reactor where chemicals are added and silica is extracted. If other minerals are present in the silica-free brine, these can be extracted, and the mineral-mined water is finally pumped to a surface pond and injected into the subsurface (Fig. 14.15).

## 14.10.4 Case study: Mammoth Pacific

In 2006, LLNL scientists, in collaboration with other agencies, worked with managers at the Mammoth Pacific power plant complex (known as MPLP) in Mammoth Lakes, California to remove silica from the geothermal water. Because the silica content of the geothermal water at MPLP is low compared to typical geothermal water, the co-produced silica is of high, marketable quality. However, the low silica content makes conventional methods for silica recovery less effective than at average geothermal facilities.

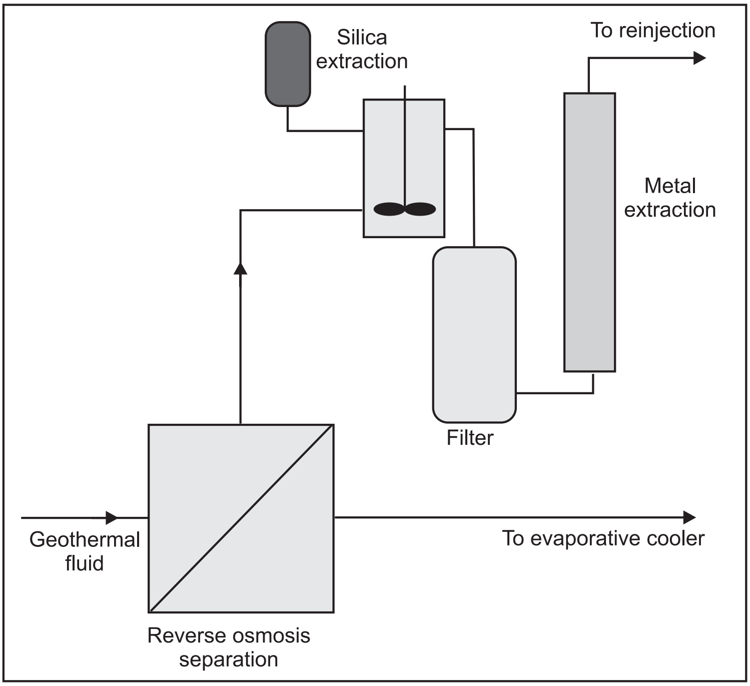



**Figure 14.15** Silica extraction diagram

To begin the silica extraction process at Mammoth, the geothermal water is tapped after passing through the heat exchanger and before injection, where it undergoes reverse osmosis. This process concentrates the silica, which then flows through a stirred reactor where salts or polyelectrolytes—synthetic chemicals used to clump solids—are added to induce silica precipitation. The simple silica molecules bond together to form colloids, which are silica particles about 10–100 nanometres in size. These larger molecules cluster to form particles that can be removed by filters downstream from the reactor. Preliminary results suggested in 2006 that silica recovery at Mammoth Lakes could reduce the cost of geothermal electricity production by 1.0′/kWh. The market value of silica that could be produced from the Mammoth Lakes site if silica is removed from all geothermal liquid is estimated to total $11,000,000/ year (as on 2006). LLNL is also considering using reverse osmosis to separate lithium, cesium, rubidium and tungsten. However, these activities have not yet been pursued.

### 14.10.5 Working fluids for Rankine Cycle Power Plants

Studies at National Renewable Energy Laboratory (NREL), Idaho National Laboratory (INL), and elsewhere have shown that mixed working fluids in binary-cycle geothermal power plants can potentially reduce thermodynamic inefficiencies in the boiler and condenser, thereby improving overall plant efficiency. Researchers have investigated various pure and mixed working fluids to optimise power conversion efficiency. One potential working fluid, especially suitable for lower temperature resources, is ammonia-water as used in the Kalina cycle.

The Kalina cycle uses a mixture of 70 per cent ammonia and 30 per cent water as the working fluid. The fluid is vapourised using the geothermal water as the heat source. Because the ammonia-water mixture boils over a range of temperatures, its temperature through the vapouriser aligns closely with the geothermal water temperature, improving the thermodynamic efficiency of the heat transfer process. However, this alignment can result in a smaller temperature differential between the geothermal water and the working fluid, which can require greater heat exchanger surface area. And while Kalina affords a higher thermodynamic efficiency because the cycle reduces so-called thermodynamic irreversibilities, the split ammonia and water streams add complexity to the system and may require additional pumping power. Plant operators and developers offer differing views about the potential for the Kalina model to improve upon Rankine-type power plant performance. However, many experts see the possibility for marketability in the future. One challenge is that the Kalina cycle has not yet been commercially verified in the US, making it difficult for developers to secure investors. A solution may be for the government to provide cost-shared projects with industry, so as to verify the viability of any new power conversion cycle. This process of cost-sharing and verification is important for all emerging geothermal technologies.

### 14.10.6 Hybrid cooling systems

Experts site hybrid cooling as one of the most important areas for surface improvements. In an increasingly water-constrained world, air cooling will likely become the preferred cooling option. However, the relative inefficiency of air-cooled systems during the summer, when the temperature differential between the air and water is reduced, has proven in some cases to be a liability. On days with extremely hot conditions, some plants put out half the power they'd produce on a cold day.

### 14.10.7 Coatings

Corrosion and deposition of mineral scale (known as fouling) can occur at geothermal resource areas with high concentrations of dissolved and suspended solids, such as the geothermal water at the Salton Sea in California. When scale accumulates over time, it can clog pipes or vessels and decrease the effectiveness of heat exchangers. Fouling can be controlled by the use of chemical additives to keep scale from forming or by periodic cleaning fouled surfaces, but these practices add to operating costs. Traditionally, expensive materials such as high-alloy steel and titanium have been used to reduce corrosion. However, these do not transfer heat well, and can cost at least three times as much as traditional materials.

In order to reduce the cost of maintaining open flow paths and efficient heat transfer, Brookhaven National Laboratory (BNL) developed durable, scale-resistant polyphenyl sulphide-based coatings for carbon steel. These coatings can be used for heat exchangers—devices which transfer heat through a conducting wall from one fluid to another—as well as for binary cycle power plants, piping, flash vessels, and other plant components. Coatings applied to carbon steel are less expensive than alloys, deliver equivalent corrosion protection, and are easier to clean than stainless steel and titanium.

When carbon steel tubes coated with a thermally-conductive coating variant were field tested by the National Renewable Energy Laboratory and compared to a high-alloy alternative, the coating variant resisted fouling and maintained heat transfer as well or better than the high-alloy. In locations where geothermal fluid is particularly mineral laden or corrosive, coated carbon steel may be a good alternative to more expensive construction materials.

Coatings are also useful with air-cooled systems. Spraying air-cooled condensers with water increases the efficiency of the system, but tends to corrode the heat exchanger fins. Researchers at BNL and NREL have therefore considered different coatings to apply to aluminium fins used in air-cooled heat exchangers to prevent corrosion.

While coatings have been used commercially in military, nuclear, and petroleum facilities, they have not yet been applied commercially to geothermal applications.

## 14.11 Direct use

Geothermal resources, through geothermal hot springs, have been used directly for centuries. Though hot springs are still used today, geothermal water can now be used directly (known as 'direct use') for an expanded variety of uses, primarily related to heating and cooling. The main utilisation categories are swimming, bathing and balneology; space heating and cooling, including district energy systems; agricultural applications such as greenhouse and soil heating; aquaculture application such as pond and raceway water heating; and industrial applications such as mineral extraction, food and grain drying.

Direct uses work best with temperatures between 70° and 300°F (21° and 149°C). Resources in this range are widespread and exist in at least 80 countries at economic drilling depths. No conversion efficiency losses result when resources are used in this range, and projects can use conventional water-well drilling and off-the-shelf heating and cooling equipment (allowing for the temperature and chemistry of the geothermal water).

Projects can be built on a small scale (mom and pop operations) such as for an individual home, single greenhouse or aquaculture pond, but can also be built on a large scale such as for district heating/cooling, food and lumber drying, and mineral ore extraction.

In modern direct-use systems, a well is drilled into a geothermal reservoir to provide a steady stream of hot water. The water is brought up through the well, and a mechanical system—piping, a heat exchanger, and controls—delivers the heat directly for its intended use.

Care must be taken to prevent oxygen from entering a direct use system, as geothermal water is normally oxygen free, and dissolved gases and minerals such a boron, arsenic, and hydrogen sulphide must be removed or isolated to prevent corrosion, scaling, and harm to plants and animals. Carbon dioxide, which often occurs in geothermal water, can be extracted and used for carbonated beverages or to enhance growth in greenhouses.

The typical equipment for a direct-use system is illustrated in Fig. 14.16, and includes downhole and circulation pumps, heat exchangers (normally the plate type), transmission and distribution lines (normally insulated pipes), heat extraction equipment, peaking or back-up generators (usually fossil fuel fired) to reduce the use of geothermal water and reduce the number of wells required, and water disposal systems (injection wells).

## 14.12 New technologies: the path forward

Regardless of advances in geothermal technology, geothermal will not provide the silver bullet solution to our energy needs. Nor will any single resource. Instead, geothermal technology advances can help increase our country's share of renewable, sustainable geothermal energy. And that's important—today, only a fraction of the geothermal resource base is tapped. Surface technology developments, in particular, can increase energy production without impacting the resource base. Technology, both surface and subsurface, can be developed a variety of ways.

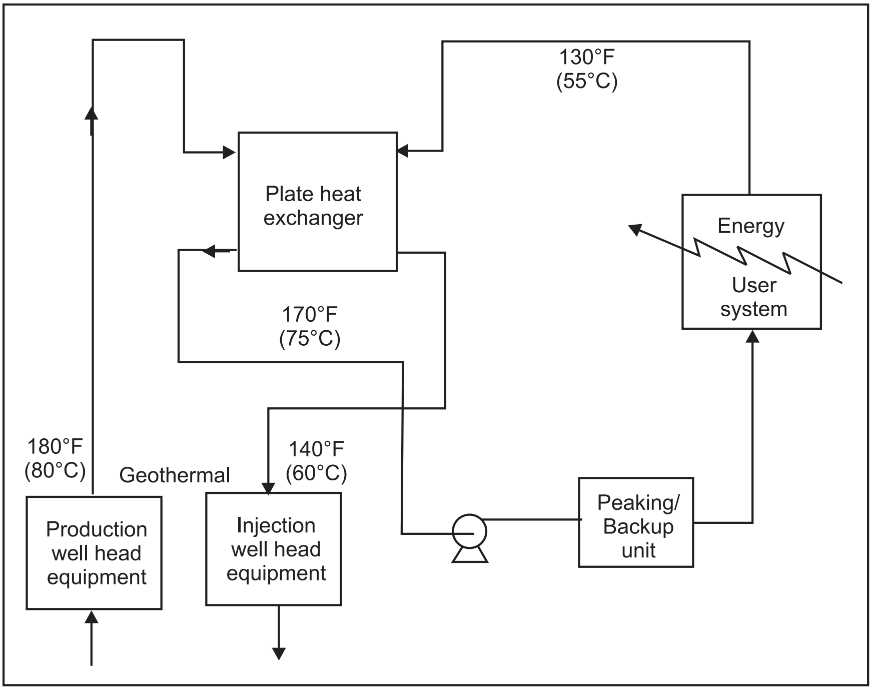



**Figure 14.16** Typical direct use geothermal heating system configuration

## 14.13 Nanotechnology and geothermal energy

Nanotechnology and geothermal energy have been hot topics lately. Currently, geothermal energy accounts for just about 0.5 per cent of energy production, but that number could rise to as much as 10 per cent in the future. Below the surface of the earth, there is a storehouse of heat, waiting to be tapped into for energy production purposes.

### 14.13.1 Challenges and controversy with commercial systems

Geothermal energy has been a topic of research that is somewhat controversial. By using the heat deep in the earth to produce energy, dependence on fossil fuels can be reduced, but is it really worth it?

Deep drilling for this resource has been shown to cause small earthquakes. Putting earthquakes aside, geothermal energy requires very high temperatures to be effective. There are only a few places in the world that could even benefit from this source of energy and they would face problems such as needing to provide antifreeze for the pipes that run the system in cold times, and the risk of pollution and altering the landscape. Thankfully, these problems have only encouraged scientists to continue research using nanotechnology to solve these issues. Solutions are being developed that uses nanotechnology, where energy can be produced from lower temperature sources. Earthquakes? Not any more. There won't be the need to drill as deeply to produce effective amounts of energy, greatly reducing the risk of earthquakes. Because of lower temperature requirements, nanotechnology and geothermal energy will make it possible to generate power in more places, making the number of people who would benefit much greater.

### 14.13.2 Solving the challenges

Many worry about the environmental effects and it is wise to evaluate the unintended consequences of any new technology. Nanotechnology has actually helped eliminate many of the effects on the environment from drilling into the earth's crust. In the past, poisonous gases have been released and land sinkage has occurred when too much water has been removed from the reservoir at the bottom of the well. The new technology has the ability to clean the gases out of the air, reducing the amount of pollution. They can also replace the water back into the ground from where it came, reducing land sinkage and reusing the resource more efficiently. What does all of this mean for you? Well, if you live in an area that can benefit from nanotechnology and geothermal energy, this means a more renewable source of energy that is cleaner and much less expensive. Your local utility company can produce cheaper electricity, lower pollution, and rely less on fossil fuels.

### 14.13.3 Nanotech tool for enhanced geothermal

Enhanced geothermal systems (EGS) could be the Holy Grail of renewable energy sources. If it works, it could potentially supply an almost unlimited amount of energy, cheaper than conventional fuels, from virtually anywhere in the world.

That is, if it works… Unlike conventional geothermal, EGS instead involves drilling much deeper, and fracturing rock kilometres below the surface to create an artificial circulation system.

Geodynamics found out the hard way that this is not so easy. Their pilot project in the Australian Outback was on-line to be the first commercial example of EGS anywhere in the world until they had a drill hole blowout last May. The project remains in limbo until a field investigation is completed. Researchers at Stanford University may have a new tool for companies taking on this very risky venture through the novel use of nanotechnology. One of the many challenges facing EGS pioneers is: how do you determine the porosity of very hot bedrock at the bottom of a very deep and expensive drill hole?

Professor Roland Horne and his grad student Mohammad Alaskar managed to pass silicon nanoparticles through solid rock, which could provide invaluable information for EGS engineers as they move their projects forward. 'Nanotechnology has found a tremendously varied number of uses', said Horne. 'And, this occurred to us to be one of them. By passing the nanoparticles through the fractures we have a way of determining how big they are and potentially other things, such as their temperature, perhaps pressure, chemistry, all of those things.'

Stanford's research is funded through ongoing support of the Department of Energy, which has made enhanced geothermal a strategic priority.

Enhanced geothermal is a potentially game-changing exciting technology. As costs and risks come down, perhaps with the help of nanotechnology, it is definitely worth keeping an eye on.

## 14.14 Summary

Geothermal surface technology is an important part of geothermal energy development. Geothermal fluid—a hot, sometimes salty, mineral-rich liquid and/or vapour—is the carrier medium that brings geothermal energy up through wells from the subsurface to the surface. It is withdrawn from a deep underground reservoir, isolated from groundwater by thickly encased pipes, making the facility virtually free of water pollution. Once used, the water and condensed steam is injected back into the geothermal reservoir to be reheated. A geothermal resource that uses an existing accumulation of hot water or steam is known as a 'hydrothermal' resource. All geothermal electricity produced today derives from the hydrothermal resource base.

Characteristics of the geothermal fluid, including temperature, chemistry, and non-condensable gas content (NCG), can influence power plant design. Two substances sometimes found in geothermal fluid, hydrogen sulphide ($H_2S$) and mercury, are regularly abated at geothermal facilities, eliminating 90–99.9 per cent of the substances.

*Power plant basics:* Like all conventional thermal power plants, a geothermal plant uses a heat source to expand a liquid to vapour/steam. This high pressure vapour/steam is used to mechanically turn a turbine-generator. At a geothermal plant, fuel is geothermal water heated naturally in the earth, so no burning of fuel is required.

*Power plant size:* Though the size of a power plant is determined primarily by resource characteristics, these are not the only determining factors. Factors that favour the development of larger geothermal plants include:

1. Cost decreases when larger quantities of materials, including steel, concrete, oil, and fuel, are purchased at one time.
2. High transmission costs, regardless of plant size, can include land use and rights-of-way fees.
3. Though some automated facilities require few personnel, a minimum number of people are typically required to run a geothermal power plant.

Factors that favour the development of smaller geothermal plants include:

1. Developers may opt to start small and increase output as they come to understand the potential of the resource through continued use.
2. Smaller plants require less time to permit.
3. The production tax credit (PTC) induces developers to construct smaller plants that can qualify for the short time frame of the PTC.
4. A developer's power purchase agreement may require that he start with a small output and gradually increase production.

*Conversion technology:* A conversion technology represents the entire process of turning hydrothermal resources into electricity. Four options are available to developers:

1. Dry steam plants, which have been operating for over 100 years, make use of a direct flow of geothermal steam.
2. The most common type of power plant, a flash power plant, uses a mixture of liquid water and steam.
3. Binary geothermal plants function as closed loop systems that make use of resource temperatures as low as 165°F (74°C). A Rankine cycle is the commercial binary cycle used in the United States.
4. A combination of flash and binary technology, known as the flash/binary combined cycle, has been used effectively to take advantage of both technologies.

*Cooling system:* Most power plants, including most geothermal plants, use water-cooled systems—typically in cooling towers. In areas with scarce or expensive water resources or where the aesthetic impact of steam plumes (produced only in water-cooled systems) are a concern, air cooling may be preferred. However, air-cooled systems are influenced by seasonal changes in air temperature.

*Structuring power plant to minimise impact:* A geothermal developer mitigates potential impacts in a variety of ways. Developers may use noise muffling equipment, visual mitigation techniques, strategies to reduce potential effects on wildlife and vegetation, monitoring activities, and regular maintenance and upkeep activities.

*Efficiency:* The public interest in energy efficiency arose as a fossil fuel issue: that is, the less fuel used per output, the fewer emissions and the greater quantity of depleting fuel conserved. For renewable energy use, in contrast to fossil fuel use, efficiency is primarily an economic concern. This is because at renewable sites like geothermal power plants, the fuel source is not burned, and thus few emissions are released. Geothermal developers choose to discuss efficiency in a variety of ways, depending upon the context in which an efficiency measurement is needed and the characteristics of the resource and plant.

Several 'non-traditional' technology applications have been considered or are emerging, that could further expand geothermal potential:

1. *Hybrid systems:* A hybrid system integrates another resource into a hydrothermal geothermal power plant, therefore creating more electricity without expanding the use of the geothermal resource. Geothermal can be used in combination with biomass, combined heat and power or CHP (geothermal electricity plus a geothermal direct use application), geothermal heat pumps, and geopressured resources (those that operate on both natural gas and geothermal fuel).
2. *Enhanced geothermal systems (EGS):* EGS resources could be harnessed using existing geothermal power systems.
3. *Oil and gas co-production:* An oilfield co-produced resource makes use of wells already drilled by oil and gas developers. These wells are either deep enough to encounter hot water, or could be deepened into hot zones.

*New technology:* Several surface technology applications look particularly promising for the future. These include:

1. *Incremental technology improvements:* Small-scale improvements can be commercially implemented more quickly than larger, more revolutionary advances, and can be incorporated into existing designs with comparatively lower risk.
2. *Increasingly standardised, modular geothermal conversion systems:* Modular components and subcomponents reduce costs because they can be pulled from off-the-shelf designs that are mass-produced. They allow developers to move ahead more rapidly with plant development and, once a plant is established, capacity additions.
3. *Mineral recovery:* Further research and development could make the separation of minerals from geothermal water, known as mineral recovery, a viable technology. Mineral recovery offers benefits such as reduced scaling and increased revenue.
4. *Mixed fluids:* One working fluid especially suitable for lower temperature resources is an ammonia-water mixed fluid system as used in Kalina and other cycles. Studies have shown that mixed

working fluids in binary-cycle geothermal power plants can reduce thermodynamic inefficiencies.

5. *Hybrid cooling:* In an increasingly water-constrained world, air cooling will likely become the preferred cooling option. However, the relative inefficiency of air-cooled systems during the summer has proven in some cases to be a liability. Hybrid cooling systems seek to integrate the best of both systems, increasing seasonal efficiency while also reducing water use and aesthetic impact.
6. *Coatings:* Traditional materials used to reduce corrosion do not transfer heat well and can cost at least three times as much as traditional materials. Researchers have engineered less expensive 'coatings' that can be applied to various power plant components to reduce scaling and fouling.

*Direct use:* Geothermal resources have been utilised for centuries through 'direct use'. Direct use resources are tapped by drilling wells and bringing hot water to the surface directly for a variety of uses, primarily for space heating, but also for drying farm and timber products, aquaculture and industrial uses. Geothermal heat pumps: According to the DOE, geothermal heat pumps (GHPs) use 25–50 per cent less electricity than conventional heating or cooling systems. Geothermal heat pumps can reduce energy consumption—and corresponding emissions—from 45 to 70 per cent when compared to traditional systems. They also improve humidity control. Because heat pumps do not require a geothermal reservoir, they can be used anywhere in the world.

## 14.15 Environmental monitoring of geothermal power plants

During the operation phase of geothermal power plants, environmental engineers and scientist are entrusted with the task of monitoring their impacts on the environment. With a well designed monitoring plan, they are kept informed of the conditions of the system which they are responsible for maintaining and a sound environmental management plan helps ensure that the monitoring is carried out in an effective manner within the boundaries of their observation space, in accordance with regulation and best practices. As is the case with the power plant engineer, the environmental engineer should strive to apply preventive measures, to ensure continued sustenance of the natural environment.

As all other anthropic projects, geothermal power plants interact with their surrounding environment in various ways over the course of their lifetime. They thus become a part of the complex planetary environment without any obvious demarcated boundaries. The impacts can vary in nature, severity and scope over the different phases of development, which according to Steingrímsson consist of a preliminary study, an appraisal study, project design and construction, commissioning and operation, and finally shutdown and abandonment. Early impacts during surface exploration are usually minimal, but they become gradually more pronounced as the project moves through exploratory drilling and on to the appraisal study phase (Fig. 14.17). The greatest impacts are brought about during the design and construction phase, when the local environment in the geothermal field and at the power plant site may change significantly with the clearing of land and the construction of man-made structures, when wells are being flow tested and the economic and social effects of the power plant are felt most profoundly in the neighbouring communities. After commissioning, the power plant usually falls into a rather steady interaction with the environment if maintenance and operation activities are carried out according to best practices. This interaction finally stops when the plant is shut down and abandoned, although there will be lingering local effects, depending on the reversibility of impacts and the degree of restoration.

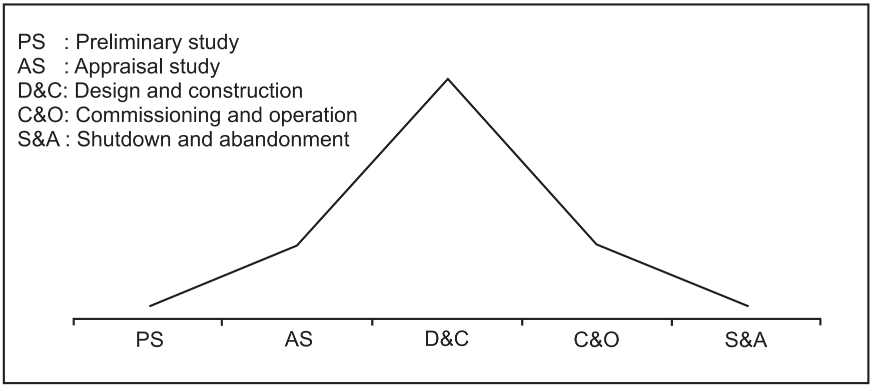



**Figure 14.17** Hypothetical relative degrees of the environmental impacts of the different phases of geothermal power plant development

The intent of this chapter is to present a broad overview of environmental monitoring of geothermal power plants in operation and to examine to a limited extent the role of environmental engineers and scientists in that context.

## 14.16 Geothermal power plants in the environment

Geothermal power plants in operation cannot be viewed as isolated systems. They rely upon high enthalpy geothermal fluids that may draw their heat content from rocks several kilometres beneath the surface of the earth—heat that may have been locked in the deep interior of the planet since its formation around 4.5 billion years ago or released from radioactive heavy elements that captured and locked away some of the tremendous energy of supernovae long before the formation of the solar system. The plants process these fluids and re-emit them to the environment in different states and compositions: water and dissolved substances are reinjected or discharged to the surface and steam and non-condensable gases are emitted to the atmosphere, where they may be advected and dispersed over long distances while undergoing chemical reactions with other atmospheric components. One of these gases is $CO_2$, which has an estimated 200 years combined lifetime in the atmosphere, biosphere, and upper ocean. Over this period, it can contribute to radiative forcing of the climate and acidification of the oceans. Geothermal power plants therefore interact with the environment over vast distance and time scales.

Geothermal power plants need cooling fluids to discard waste heat to the environment. These can be fresh or salt water that makes a one-time pass through a condenser, carrying the waste heat into a nearby river, lake or ocean. The cooling fluid can also be water that carries waste heat into the environment in latent form through an evaporative process in a cooling tower or air that cools a dry condenser. The first method increases the temperature of the receiving river, lake or ocean, which may affect the biosphere, the second increases the temperature and humidity of the local atmosphere and the third increases the temperature of the local atmosphere.

In addition to geothermal fluids and cooling fluids, a geothermal power plant in operation needs to discard various substances, materials and equipment and new ones are required for maintenance purposes. A pump made by workers in China may be bought for maintenance in a power plant in El Salvador, Iceland or Kenya, and transformer oil or cooling water treatment chemicals may likewise be shipped between continents. Last, but not least, geothermal power plants may provide electricity to the public and industry on a country-wide scale and hot water to district heating systems on a municipal scale, thereby affecting the social and economic fabric in these spaces. It is thus clear that geothermal power plants in operation affect the environment and socio-economic sphere near and far.

A common practice in environmental engineering, fluid mechanics and thermodynamics is the application of control volumes to systems of interest. They can range from the infinitesimal to the very large depending on the problem at hand and are used for simplification to draw an arbitrary border between the system of choice and its surroundings. The goal is usually to bundle the various processes of the system within the control volume together without regard to the details of system components. The interaction of such systems with the surrounding environment can be evaluated on the basis of mass, energy or information exchange through the imaginary borders of the control volume.

One way of selecting the control volume, or observation space, of a geothermal power plant is to imagine the borders as consisting of the land surface and the borders of man-made structures and equipment, or perhaps extending them below the surface to the casings of wells (Fig. 14.18). This may be the preferred observation space of power plant engineers who are concerned with daily operations and maintenance of their power plants. In order to keep the plants in optimum shape for future operations, they may apply preventive maintenance philosophies within this space, since the key to reliable operation is constant monitoring and condition-based maintenance. In such an observation space, the environment may be a concern primarily as an outside agent of influence on the system of relevance (the power plant), as weather conditions and the chemistry of surrounding fluids may detrimentally affect equipment and materials.

The environmental engineer may take the stance of looking at a bounded or unbounded observation space surrounding the power plant to look at the effects of the plant on the environment. In this case, the power plant has become the outside agent of influence on the system of relevance, which is the environment, often extended to the socio-economic sphere. The environmental engineer is concerned with sustaining the environment, so that it is passed on to the future in the same or better shape than at present. As one synonym of the verb to 'sustain' is to 'maintain', the goals of the power plant engineer who seeks to maintain his system in optimum working condition is analogous to that of the environmental engineer who seeks to sustain the system which he or she is responsible for monitoring.

In this respect, it is important to note that the environmental engineer may choose to look at details or overall effects within the observation space. An example is the clearing of a patch of land and the associated loss of vegetation and wildlife, which may or may not be considered acceptable depending on the scarcity of the affected flora and fauna and the magnitude of the effects, but which may possibly be compensated for by restoring another patch of land to similar conditions. Therefore sustained balance of the system on a predetermined scale is sometimes what should be sought rather than simply keeping individual small scale parts of the system in sustained condition.

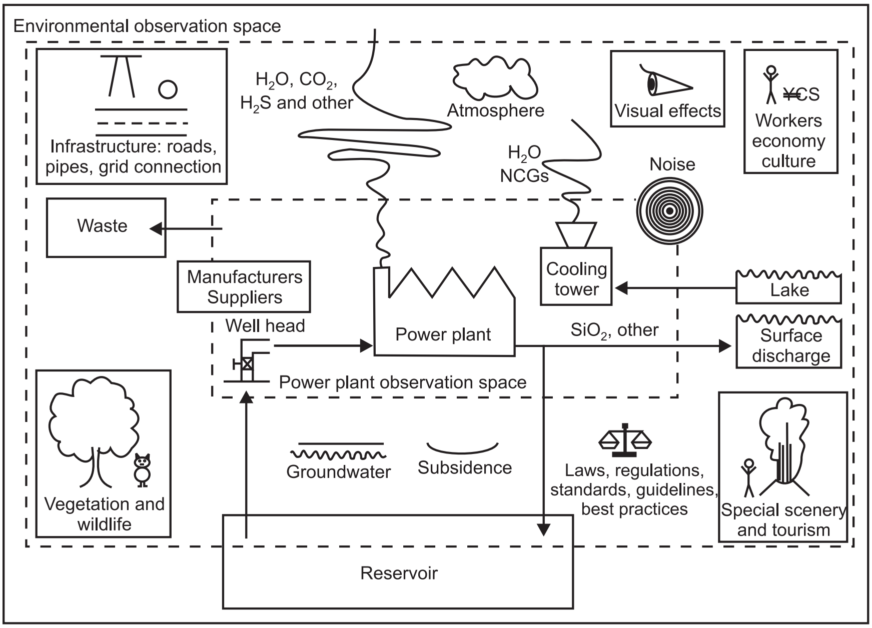



**Figure 14.18** A simple presentation of one possible demarcation of the environmental and power plant observation spaces.

While arbitrary compartmentalisation into observation spaces can be useful, it should be remembered that the power plant and its surrounding environment can also be viewed as a single system of interacting parts and perhaps such an approach is most fit.

## 14.16.1 Interaction with the environment

The interaction between geothermal power plants and the surrounding environment can be divided into the impacts of the power plants on the environment and the impacts of the environment on the power plants. Kristmannsdóttir and Ármannsson have classified the former into the following categories:

1. Surface disturbances
2. Physical effects of fluid withdrawal
3. Noise
4. Thermal effects
5. Chemical pollution
6. Biological effects
7. Impact on (protected) natural features

Surface disturbances include the clearing of land, changes in landscape and the introduction of man-made structures where none existed before. Physical effects of fluid withdrawal include subsidence, lowering of the groundwater table and induced seismicity as earth layers consolidate due to the removal of fluids from matrix pore spaces or when increased pressure due to injection causes the relief of accumulated geological stresses. Thermal effects include elevated temperatures of rivers, lakes and groundwater due to thermal fluid discharges and changes in cloud formation and local weather due to steam emissions. Chemical pollution can be caused by steam and non-condensible gas emissions to the atmosphere and the discharge of brine to surface or subsurface water bodies. All of these have the potential of impacting wildlife, vegetation and the socio-economic sphere around a geothermal power plant, as well as altering natural features for the short-term or permanently. Monitoring and controlling sources and their impacts is therefore of utmost importance.

On the other hand, the impacts of the environment on geothermal power plants include:

1. The application of external dynamic forces to power plant structures. These include seismic forces changing over short time scales and deforming forces that may change over much longer time scales due to subsidence. Wind (hurricanes), floods, snow and ice are also examples of dynamic environmental forces that may follow a seasonal pattern and affect power plant structures.
2. Degradation of equipment and materials due to environmental chemistry. These effects include corrosion and scaling.

All of these effects need to be monitored to maintain and sustain the power plant and its environment.

### 14.16.2 Environmental monitoring

The goal of environmental monitoring is to keep the environmental engineer informed of the conditions of the system which he/she is responsible for maintaining. Ideally, information about all possible factors of concern should be available at all times to give instantaneous snapshots of the system when needed. The environmental engineer, however, does not have the same elaborate monitoring and control system at his/her disposal as the power plant engineer, where the most important parameters of power plant operations are constantly monitored and recorded, and can be viewed on a display in a central location. While such frequent information may be obtained by chemical, meteorological and seismic sensors in the environment, the environmental engineer will in most cases have to make his/her own observations and measurements. As this can be costly, it is important to design a well structured monitoring program that fulfills the demands of regulations and best practices, while minimising cost. Quality of data should be emphasised over quantity, since data volume by itself is not an indicator of meaningful information, but rather the context in which the data is collected and how it is related to processes of interest.

In 2007, the World Bank Group (WBG) listed the common components of a pollution monitoring program in the following manner:

The elements of a monitoring plan normally include selection of the parameters of concern; the method of collection and handling of samples (specifying the location, the frequency, type, and quantity of samples, and sampling equipment); sample analysis (or alternatively, online monitoring); and a format for reporting the results.

While pollution monitoring is essentially the monitoring of various chemical species and other potentially harmful agents (such as particulate matter) in the environment and unmistakably important in the context of geothermal power plants, it is only a part of a thorough and well rounded geothermal environmental monitoring program. The WBG description is therefore not complete in the context of geothermal power plants, but can nevertheless serve as a basis that can be extended to the other factors of concern to design a sound environmental monitoring program.

According to the WBG, 'an environmental management system is a structured program of continuous environmental improvement that follows procedures drawn from established business management practices'. One such system is the ISO 14000 series, which helps delineate well organised management programs. As it provides structure more than content, it leaves the responsibility of identifying environmental concerns to the users of the system. The ISO 14001 environmental management system has for example been implemented by Instituto Costarricense de Electricidad for the Miravalles power plant in Costa Rica and has allowed continuous improvement in controlling the environmental impacts of the power plant.

In order to clarify the goals of monitoring and establish the content of an environmental management plan, it can be helpful to keep the following basic questions in mind:

1. What aspects need to be monitored?
2. Why are they a concern?
3. Where should the monitoring take place?
4. How should monitoring and analysis be carried out?
5. When is monitoring needed?

While environmental monitoring programs can be designed meticulously, they are meaningless without references to compare observations against, and these mainly take two forms:

1. The natural state before alteration.
2. Laws, regulations, standards, codes, guidelines, and best practices.

### 14.16.3 Baseline establishment

It is necessary to know the natural state of the environment before it is changed by exploration, testing or utilisation. Baseline data collection involves collecting background information for this purpose on the physical, chemical, biological, social and economic settings in the vicinity of a proposed geothermal power plant and is usually carried out as part of scoping or an environmental impact assessment. The information may be obtained from secondary sources or gathered through measurements, field samplings, surveys, interviews and consultations. A well-established baseline allows the environmental engineer to assess how significantly specific environmental conditions deviate from the natural state during the power plant operation phase and to what extent they are caused by the plant.

### 14.16.4 Role of laws, regulations, standards, codes, guidelines and best practices

Most countries have established specific laws that address the environment, and environmental regulations may be issued by relevant ministries. The particular aspects addressed and the detail in which they are covered can however vary from country to country. Power plant designers and operators may be obliged to follow certain standards, norms and codes that may be relevant to the environment, and financing institutions may condition the financing of projects to the observation of environmental guidelines that they have established. Companies and developers can also decide on their own accord to follow best practices without being obliged to do so by outside parties.

Environmental laws are important in channelling and placing constraints on human interaction with nature. Governmental and municipal regulations are an extension of the law, which may address specific topics in more detail than the laws themselves and dictate limits, such as the allowable concentration of pollutants in the environment. They may also provide a framework for the development of geothermal resources and address issues as diverse as planning, the acquisition of land, the application of concessions, exploration, exploitation, rights, permits, performance guarantees, taxation, general procedures and obligations of actors.

Engineers may be constrained by standards and codes in their design work that are pertinent to the environment. Civil engineers who design concrete containment structures for conveying, storing or treating liquid or solid wastes may for example have to take account of specific codes in structural design and materials selection in order to ensure that those wastes will not find their way into the environment.

Health guidelines are important to the environmental engineer as they often provide advice on maximum allowable concentrations of particular pollutants over a set time period. Such guidelines are issued by national agencies or international organisations such as the World Health Organisation (WHO) and are often specific to the fluid medium carrying the pollutants, such as the atmosphere or water bodies. One of the tasks of the environmental engineer is to assess measured concentrations against such guidelines and to devise mitigation schemes if they are surpassed.

### 14.16.5 Environmental engineering and mitigation

It is important that environmental considerations be taken into account from the very first stages of geothermal resources development and that these considerations are noted in the design of a power plant. To this end, it is important to start gathering environmental baseline information as soon as possible and that an environmental impact assessment be carried out—the results of which will be of use in the power plant design. If environmental constraints are likely to be broken based upon available information about the geothermal fluid properties and composition and initial proposals for utilisation, it is the task of the environmental engineer to devise schemes to prevent such scenarios from unfolding. A geothermal power plant that is well designed with regard to the environment and well managed is not likely to cause environmental harm. However, as regulations and guidelines may change and conditions become more stringent with time, the environmental engineer must keep abreast of developments in the regulatory sphere that may increase environmental demands on a power plant, even if the operation remains in a steady phase.

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# Advanced Renewable Energy Systems

## Part II

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# 15

# Geothermal energy resources and its potential in India

## 15.1 Introduction

The 'energy crisis' in the seventies and onward changed the approach and priorities in the field of discovery of new non-conventional energy resources. It enhanced the efforts by various countries to look for alternate indigenous and renewable energy resources. In the process wind energy, solar energy, geothermal energy and sea wave energies were tried and developed as non-conventional energy resources in various countries depending upon their requirements.

Thermal springs have been known to occur in India since centuries. At places, like Badrinath and Gangotri in Uttarakhand, Sohna in Haryana, Rajgir in Bihar, Bakreshwar in West Bengal and Ganeshpuri in West Coast, Maharashtra, temples have been built on thermal springs and thermal water was utilised by locals. Thermal springs have drawn attention, being the surface manifestation of the vast resources of geothermal energy at depth in the form of geothermal reservoirs. Italy, being the pioneer country produced electrical power from geothermal fluids, way back in 1904. At present (as on year 2007) the total estimated electric power production from geothermal energy is in the range of 8771 MWe all over the globe, which includes USA, Philippines, Mexico, Italy, Japan, Indonesia, New Zealand, El Salvador, China and Costa Rica. In the nonelectrical sector, the thermal water is used in greenhouse cultivation, space heating, paper and pulp industry, agriculture industry, fish farming, tourism viz. bathing and swimming, etc. In India, almost all the three hundred thermally anomalous areas have been examined and assessed for geothermal potential. The temperatures of these springs range from 35°C to the boiling point of water at that height. Thirty-one areas have been examined in detail and finally, shallow drilling has been done in sixteen areas. Systematic efforts to explore the geothermal energy resources commenced in 1973 with the launch of Puga geothermal project and gradually the exploration work was extended to cover Chhumathang, Ladakh, J&K; Parbati valley, HP; Sohna, Haryana; West Coast, Maharashtra and Tattapani, Sarguja, Chhattisgarh. Six areas, four in Himalayas and two in Peninsula, hold promise for utilisation for either electrical power generation or direct heat applications on industrial scale. The deepest exploratory bore holes have been drilled up to a depth of

385 m at Puga, Ladakh, J&K; 220 m at Chhumathang, Ladakh, J&K; 700 m at Manikaran, Himachal Pradesh; 728 m at Tapoban, Uttarakhand and 620 m at Tattapani, Sarguja, Madhya Pradesh. As a result, it was deduced that the total thermal discharge from springs and drill holes is 30 litre/second and 250 tons/hour at Puga, Ladakh, J&K; 5 litres/second and 50 tons/hour at Chhumathang, J&K, Ladakh; 15 litre/second and 100 tons/hour at Manikaran, HP; 15 litre/second and 150 tons/hour at Tapoban, Uttarakhand and 1 litre/second and 120 tons/hour at Tattapani, Chhattisgarh respectively (Geothermal Energy Resources of India, 2002 and references therein). The exploration endeavour also pointed to the favourable geological-hydrogeological setup in these geothermal fields, which have the possibility of encountering sizeable geothermal reservoirs which could sustain electrical power production on MW scale and nonelectrical utilisation projects on a commercial scale.

## 15.2 Geothermal system

On the basis of enthalpy characteristics, the geothermal systems in India, can be classified into medium enthalpy (100–200°C) and low enthalpy (<100°C) geothermal systems. These are described as follows.

### 15.2.1 Medium enthalpy geothermal energy systems

The medium enthalpy geothermal energy resources are associated with:

1. Younger intrusive granites as in Himalayas, viz. Puga-Chhumathang, Parbati, Beas and Satluj Valley geothermal fields.
2. Major tectonic features/lineaments such as the West Coast areas of Maharashtra; along the Son-Narmada-Tapi lineament zone at Salbardi, Tapi; Satpura areas in Maharashtra; Tattapani in Chhattisgarh and Rajgir-Monghyr in Bihar, Tatta and Jarom in Jharkhand and Eastern Ghat tracts of Orissa.
3. Rift and grabens of Gondwana basins of Damodar, Godavari and Mahanadi Valleys.
4. Quaternary and tertiary sediments occurring in a graben in the Cambay basin of West Coast.

### 15.2.2 Low enthalpy geothermal energy systems

The low enthalpy geothermal energy systems are associated with:

1. Tertiary tectonism and neotectonic activity
2. Shield areas with localised abnormal heat flow, which is normally very low

## 15.3 India's geothermal resources

Physiographically, India is divisible into three distinct geographical units, viz. the Extra-Peninsular Region, Indo-Gangetic Plain and the Peninsular Region. A variety of rocks ranging in age from Archaean to Holocene are exposed in these geographical units. The thermal springs have been classified on the basis of their occurrence in specific geotectonic setups and have been grouped under different Geothermal Provinces. The geological and structural criteria that have been used in the identification of the prospective Geothermal Provinces are:

1. Occurrence in an orogenic belt, which has undergone Cenozoic folding and upliftment.
2. Occurrence in structural depressions/grabens, associated with late tertiary and quaternary upliftment in non-orogenic belts.
3. Related to deep fault zones associated with recent seismicity.
4. Occurrence in the areas of tertiary or quaternary volcanic activity.

The orogenic and non-orogenic geothermal energy resources of India are grouped as follows:

### 15.3.1 Orogenic regions

The orogenic regions are further divided into different provinces:

1. Himalayan Geothermal province (Northwest and Northeast sub-provinces)
2. Andaman-Nicobar Island geothermal province

### 15.3.2 Northwest Himalayan geothermal subprovince

This subprovince has been divided into three belts on the basis of occurrences of thermal springs. These are the trans-Himalayan belt, the central Himalayan belt and the outer Himalayan belt. This subprovince encompasses the states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand. The thermal springs occur at altitudes of 4000 to 4400 m in Trans-Himalayan belt, at Chhumathang and Puga, while in central Himalayan belt, the altitude ranges from 1300 m to 3000 m in Parbati, Beas and Satluj Valleys in Himachal Pradesh and 1000 m in outer Himalayan belts. Some of the important thermal fields are described below:

Puga geothermal field: The Puga area is located at a distance of about 180 km from Leh in Ladakh Region of J&K across the Great Himalayan Range at an altitude of 4400 m amsl. Hot spring region is located along the collided junction of two crustal plates, which were involved in the Himalayan Orogeny. Intense basic to ultrabasic, plutonic and submarine volcanism of middle to upper Cretaceous age (ophiolites suite of rocks) and several phases of widespread acid igneous activity from upper Cretaceous to upper Tertiary times have been identified.

Thermal manifestations in the form of hot springs (Fig. 15.1), hot pools, sulphur condensates, borax evaporates have an aerial extent of 4 km. Hot springs with temperatures varying from 30°C to 84°C (boiling point at Puga area) and with discharge ranging up to 300 litres/min. are present. The hottest thermal spring shows a temperature of 84°C and the maximum discharge from single spring is 5 litre/second. In addition, hot patches and minor hot water seepages are also noticed in the thermal area. Typical cones of extinct hot spring deposit exist in the eastern part of the area. Borax evaporates occur as loose deposits on the surface while the sulphur condensate fills the joints and cracks (Fig. 15.2).

**Figure 15.1** Puga Geysers attempt at commercialisation

Geophysical surveys have reported a major low resistivity zone (2–10 ohmm) in the southwestern part of the Puga geothermal area, which are indicative of the presence of thermal water in the subsurface.

Thermal waters of Puga field are near neutral to weakly alkaline-pH 6 to 8.3. Major cations and anions, in the order of decreasing concentrations, are Na, K, Cs, Li, Mg, Rb, Fe, and $HCO_3$, Cl, $SiO_2$, B, $SO_4$, As, $NH_3$, respectively. The water is essentially $NaHCO_3Cl$ type. High concentration of Li, Rb and Cs also suggests indirectly that thermal waters have stayed for longer period underground permitting intensive water-rock interaction. Geochemical thermometers, based on the concentration of Na, K, Ca and Mg, have pointed to the possibility of having thermal fluids of 220–260°C temperatures at deeper levels whereas the oxygen isotope thermometry places this estimate at 180°C. Marked Oxygen-shifts depicted by Puga thermal water is a strong indication of presence of high temperature zones at depth. Stable isotope studies on oxygen and hydrogen carried out on thermal water have clearly pointed out that these waters are meteoric in origin.

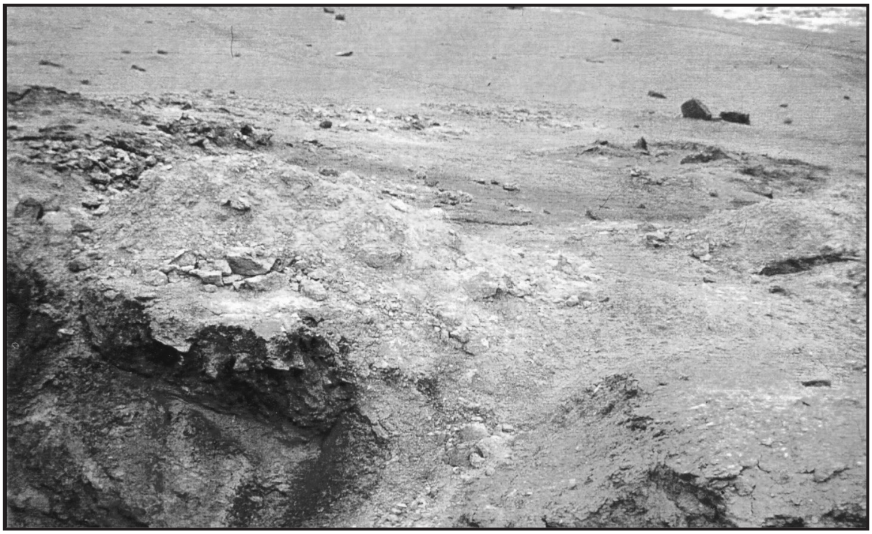


**Figure 15.2** Sulphur deposit at Puga

The thermal logging of the geothermal wells indicates an abnormally high geothermal gradient generally from 0.35°C/m to 2.5°C/m, although higher values up to 6.8°C/m have also been encountered locally. On the basis of the available thermal gradient data and a few thermal conductivity determinations, the minimum heat flow in the Puga valley has been estimated to be over 13 HFU; that is, about eight times the normal heat flow from the earth's crust. A total of 34 boreholes ranging in depths from 28.5 m to 384.7 m have been drilled in Puga valley. The bore holes that struck steam-water mixture from shallow geothermal reservoir have yielded 10 to 15 per cent of steam at a temperature up to 140°C and a pressure of 2 to 3 $kg/cm^2$. Of the 17 flowing bore holes, wellhead measurements was carried out on 8 bore holes indicating a total discharge of 190 tons/hour of water-steam mixture. The maximum discharge from a single drill hole is 30 tons/hour.

Experimental space heating and refinement of borax and sulphur have been successfully tried utilising the geothermal fluids at Puga from the shallow wells drilled so far. The extraction plant could handle 1 ton of borax ore per day and the refining plant could handle 500 kg of borax per day. Space heating experiment carried out at Puga has proved quite successful. A prefabricated hut 5 m × 5 m × 2.5 m was heated with thermal fluids and an excess temperature of 20°C over the ambient temperature could be maintained within the hut. Experimental space heating, greenhouse cultivation and poultry farming have also been successfully conducted by the GSI and RRL (Jammu). The thermal waters have been used for hatching poultry and for growth of mushroom in a hut in 500 sq m areas by the RRL, Jammu. Puga fluid has one of the highest cesium concentration (10 mg/l) in the world. Efforts were applied on to separate this valuable metal from geothermal fluid using the resin developed by BARC (Mumbai).

Puga geothermal field is the only field capable of producing either primary cycle electrical power or binary cycle power at present, though on a very small scale. However, reservoir simulation studies have suggested the possibility of generating over 3 MW electric power, if deeper levels are probed at least up to the depth of 500 m.

*Chhumathang geothermal field:* Chhumathang field is about 40 km north of Puga. It is located at a distance of 150 km from Leh, Ladakh, on Leh–Chushul road at an altitude of 4300 m. Geologically, area exposes a thick sequence of shallow marine to fluvial sediments deposited over granitic basement. These rocks range in age from Cenomanian to Miocene. The Chhumathang geothermal field is located in this belt.

SP, magnetic, seismic refraction, and resistivity surveys have been carried out. AMT surveys indicated a low resistivity zone of 13–30 ohmm up to a depth of 300 m. Geothermal area is characterised by spectacular development of spring deposits. These are in the form of carbonate plateaus up to 100 m diameter and attaining a height of 6–10 m (Fig. 15.3). Their presence gives clue to much vigorous thermal activity in the past in an area at least twice that of today's convective flow.

Thermally anomalous area stretches for about 700 m along the right bank of Indus River in the form of hot springs, travertine deposits and stained ground. Hot springs with temperatures ranging between 30° and 87°C (boiling point at Chhumathang) and many $H_2S$ emitting hot spring water pools are the surface manifestations. The maximum temperature of the thermal spring recorded is 87°C with a discharge of 1.5 litre/second. The cumulative discharge of all the springs is 200 litre/min.

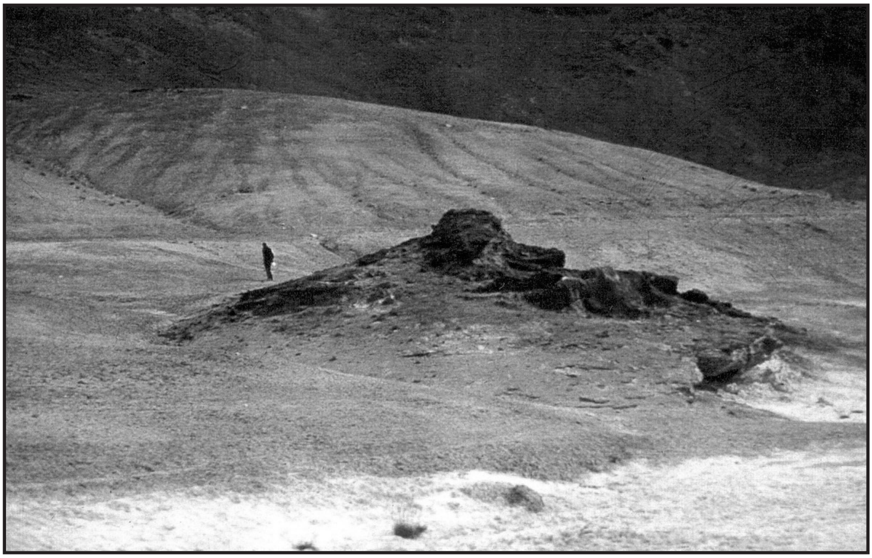


**Figure 15.3** Carbonate plateaus at Chhumathang field

Geochemical studies have indicated the existence of thermal fluid in the reservoir of about 150°C temperatures. The possibility, however, cannot be ruled out that thermal discharges are steam-heated re-equilibrated fluids and estimated reservoir temperatures pertain to shallower levels of latest chemical equilibrium. Six boreholes ranging in depth from 20–221 m have been drilled in the Chhumathang area. A temperature of about 109°C was recorded in flowing wells. Cumulative discharge from 4 flowing wells is about 50 tons/hour. The shallow geothermal bore holes drilled at Chhumathang have indicated very high temperature gradient ranging from 0.7–2.5°C/m.

Chhumathang thermal waters resemble with Puga thermal waters but differ from them in having relatively higher pH and sulphate. Stable isotope studies on oxygen and hydrogen carried out on thermal waters have clearly pointed out their meteoric origin. Chemical thermometry has pointed out deep reservoir temperature of 150°C. Geothermal energy was utilised at Chhumathang successfully for greenhouse cultivation and space heating. A temperature of 20–25°C could be maintained inside the greenhouse with outside atmospheric temperature as low as –35° to –40°C in winter. A variety of vegetables were grown.

*Manikaran geothermal field:* Manikaran geothermal field is located about 50 km east of Kulu, Himachal Pradesh at an altitude of about 1700 m. The field is located to the southwest of the Central Crystalline Axis, which runs along the great Himalayan range and comprises predominantly foliated gneiss intruded by younger granite, where profuse igneous activity has taken place during Tertiary period. The hot springs at Manikaran are located in the Manikaran quartzite (Devonian) beneath the Main Central Thrust. The granites intruding the Manikaran quartzite are possibly the source of heat of the hot-spring waters. The Manikaran quartzite is highly jointed, and these joints hold great significance as far as the movement of hot waters is concerned.

Geothermal activity at Manikaran occurs in the form of hot springs, over a distance of about 1.25 km on the right bank of Parbati river whereas on the left bank, this activity manifests itself over a distance of about 450 m. Thermal springs located on the right bank are in the temperature range of 34–96°C, whereas on the other side temperature ranges 28–37°C.

The geophysical surveys have indicated a zone of positive SP associated with low resistivity. Geothermally anomalous zone is characterised by apparent resistivity in the range of 30–100 ohmm. Thermal water is feebly alkaline with pH value ranging from 7.5 to 8.1. On the basis of dominant cations and anions, the Manikaran thermal water is $NaHCO_3Cl$ type and $NaCaHCO_3Cl$ type. A comparison of relative chloride, bicarbonate and sulphate contents shows that Manikaran water to be very similar to the thermal water discharging at Puga, a definitely higher temperature system, but without any obvious relationship. Geochemistry indicated a thermal water of about 120±10°C in the subsurface. Nine boreholes have been drilled at Manikaran and the deepest being 707 m. Maximum discharge from a single spring is about 7 litre/second. The cumulative thermal discharge from 8 bore holes is 100 tons/hour with temperature ranges from 45°C to 96°C.

Distribution of major high temperature (96°C) thermal springs and bore holes are on the right bank as compared to lower temperatures (45°C) hot spring and drill hole on the left bank point to the inflow of thermal water from northern side.

As far as the utilisation aspects are concerned, a 7.5 ton capacity cold storage plant based $NH_4$-absoption system was set up. A 5 kW pilot power plant based on binary cycle (ISO-Butane) principle was also made test run. In addition, the tourist complex could be developed in the region utilising the geothermal fluids for hot water baths, spas, etc. The thermal waters are seen to be free in respect of large scale corrosion and scaling.

*Tapoban geothermal field:* Tapoban Geothermal area is located in Dhauli river valley, a major tributary to Alaknanda river. It is approachable by an all weather 15 km long road from Joshimath, in Chamoli district, Uttarakhand at an altitude of about 1800 m. The surface manifestation is in the form of five hot springs spread over a distance of one km along the hill slopes on the left bank of Dhauli river. The highest temperature recorded is 65°C. The discharge from these springs varies between 0.83 and 9.22 litre/second. No secondary deposition is observed. Only one spring has gaseous emanations. The thermal springs emerge through Tapoban quartzite belonging to the Helang formation (Fig. 15.4).

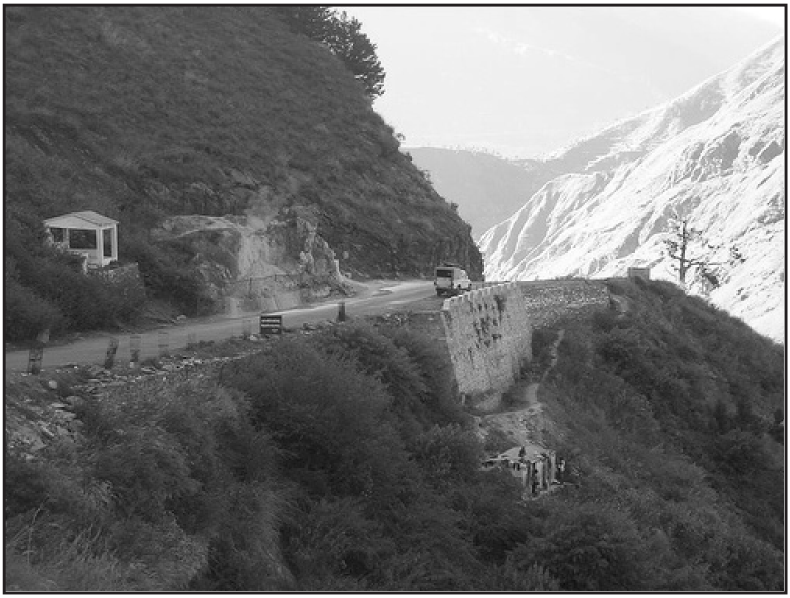


**Figure 15.4** Tapoban geothermal field, Chamoli district, Uttarakhand

The rocks exposed in the area comprise quartzite with occasional schistose bands, a thick sequence of gneiss, schist, migmatites, phyllite, limestone and quartzite of the Tethyan sequence. Geophysical Surveys have indicated low resistivity (100 ohmm) zones extending down to 165 m depth.

Geochemical studies indicate that the thermal water is neutral with pH ranging 6.9–7.2. The cations in decreasing order of concentration are Ca, Mg, Na, K and $HCO_3$, $SiO_2$, $SO_4$, Cl, B and F. The water is of Ca-Mg-$HCO_3$ type. Only one spring has gaseous emanations. The gas sample collected comprises 78.6 per cent $CO_2$, 18.96 per cent $N_2$ and 2.4 per cent $O_2$.

Secondary deposits were precipitated around the collar of the bore hole at Tapoban. The major mineral is aragonite, while quartz, alkali feldspar and mica are present in trace amount. The temperature of water was around 80°C. The geothermal system provides an example of 'Normal Gradient Heating Model'.

Chemically the thermal fluid at 92°C is indistinguishable from local cold springs, except for higher $SiO_2$ concentration in the former. The fluid descending from higher altitudes (at least 2 km above the discharge level) has attained heat under normal thermal gradient conditions. Lower temperatures and chemical inertness of quartzite have resulted in lack of water-rock interaction reflected in no significant change in fluid chemistry. Four boreholes of the depth ranging from 291 to 728 m have been drilled in the area. All the boreholes struck artesian conditions. Cumulative discharge from four boreholes is about 150 tons/hour. Highest measured temperature in the borehole discharge is 92°C.

Base temperature calculated by Na-K-Ca geochemical thermometry is 65°C. As indicated earlier, with the drop in temperature by 34°C, within a distance of 1.5 m from the bore hole, the chemistry has undergone a very significant change. Silica has precipitated so fast that the base temperature of around 150°C calculated on silica thermometry for the water samples has come down to around 90°C. Similarly ratios of Ca, Na and K have also changed drastically with the drop in temperature (causing quick precipitation).

### 15.3.3 Northeast Himalayan geothermal subprovince

Thermal springs located in Sikkim are an integral part of 'Himalayan geothermal province'. Five thermal springs located at Yumthang, Yumesamdong, Borong, Polot and Rishi are distributed in the North, South and West districts of Sikkim. The springs range in surface temperature from 38°C to 59°C with moderate discharge and can only be applicable for direct utilisation to promote non-conventional energy resources. The spring discharges have medicinal values due the presence of sulphur and boron contents. The discharges presently are used locally for drinking and bathing purposes.

Non-orogenic regions

The different non-orogenic are given below:

1. Cambay graben geothermal province
2. Son-Narmada-Tapi graben geothermal province
3. West Coast geothermal province
4. Damodar valley geothermal province
5. Mahanadi valley geothermal province
6. Godavari valley geothermal province
7. North Indian Peninsular geothermal province
8. East Indian geothermal province
9. South Indian geothermal province

Some of the important non-orogenic geothermal fields are described below:

*Tattapani geothermal field:* The Tattapani geothermal field is located 100 km northeast of Ambikapur, Sarguja district, Chhattisgarh. Tattapani is most promising geothermal field in the Peninsular India. Geothermal activity is seen in the east at Tattapani and in the west at Jhor, which are located 50 km apart. Thermal manifestation at Tattapani is very intense in an area of 0.05 sq. km with several hot spots, hot water pools and a marshy land (Fig. 15.5). The surface manifestations show occurrence of white to dirty white deposit (identified as silica) and moderate to low gas activity. The temperature of the hot water varies from 50°C to 98°C. Surface flow of the individual springs is very low while the cumulative discharge is around 60 litres/min. Indications of palaeo-geothermal activity are seen in the form of altered clay and hydrothermal deposits at a place 500 m west of the thermal activity. Tattapani geothermal field has two distinct lithological sequences belonging to Proterozoic and Gondwana Supergroup. Proterozoic rocks are widespread while Gondwana rocks are exposed at Tattapani and further west. Proterozoic rocks comprise grey and pink gneiss, augen gneiss, granulite, kyanite schist, sillimanite schist and hornblende gneiss. Phyllite, carbonaceous phyllite also forms part of the sequence. Gondwana Supergroup comprises green splintery shale; sandstone and shale alternations with coal streaks and plant fossils, reddish brown sandstone and grit bands.

**Figure 15.5** Geyser at Tattapani geothermal field, Sarguja district, Chhattisgarh

Gravity, electrical, magnetic, resistivity, self potential and AMT surveys were conducted in area. The AMT surveys indicated a conductive zone in the subsurface close to the hot spring area, which may correspond to the hot water bearing formation. Two distinct types of waters have been identified, on the basis of proportion of cations and anions in Tattapani area, i.e. Ca-Mg-$HCO_3$ and Na-$HCO_3$-Cl-$SO_4$ types. The thermal water from springs and bore holes show high fluoride content and low TDS. Higher concentration of fluoride is attributed to leaching of fluoride from hornblende of the hornblende granite. Subsurface temperature using different thermometries is at variance with each other being 120°C to 150°C. Hydrothermal alterations due to geothermal activity occur as encrustations around the hot springs, in hot water marsh, along joints, cracks and vug fillings in the country rock and breccia. Quartz, chalcedony, cryptocrystalline silica, stilbite, montmorillonite, traces of calcite and pyrite are present as the main alteration minerals. The hydrothermal mineral assemblage is in equilibrium within a temperature range of 100°C ± 10°C. Occurrence of low temperature alteration minerals in the high temperature zones suggests low water- rock ratio.

Twenty-six bore holes have been drilled to depths ranging from 100 to 620 m. Blow out conditions occurred in five wells. Bore hole GW-6 is the deepest well drilled to a depth of 500 m. The shut-in temperature of the thermal fluids is around 112°C. The cumulative discharge from wells is 1600 litres/min. About 4 kg/$cm^2$ pressure has been measured by ONGC in all the five bore holes.

Based on the cumulative discharge of 1600 litres/min. of thermal water (100°C) from five drill holes at Tattapani a joint project of ONGC-GSI-MPUVN (Madhya Pradesh Urja Vikas Nigam) to install a 300 kWe binary cycle power plant is under consideration.

Keeping in view the remoteness of the area it is essential to utilise the thermal fluids for non- electrical purposes. Thermal waters can be used for Cocoon boiling for extraction of silk thread, mushroom culture, cold storage, food processing, spa and tourist development, drying and canning of fish, rice bran oil and space heating during winter season.

West coast hot spring belt: Sixty thermal water springs occur at eighteen localities in the West coast hot spring belt. This belt extends along the West coast for a distance of about 350 km from Koknere, north of Mumbai, to Rajapur in the south, with an average width of 20 km, (maximum width 50 km in the northern part and minimum of 10–15 km in the southern part). This belt falls in Thane, Raigad and Ratnagiri districts of Maharashtra. The NNW-SSE trending belt is hilly and covers basinal areas of seven westerly flowing rivers. The eastern boundary is marked by mighty scraps of Sahyadri Mountain commonly known as Western Ghats while its western margin is marked by coastline of the Indian Ocean. The thermal spring localities have been divided into three distinct clusters in the West coast, viz.

1. Northern sector consists of six hot springs located at Koknere, Paduspada, Haloli, Sativli, Ganeshpuri and Akloli.
2. Central sector consists of four hot springs located at Sov, Vadavli, Pali and Unhavre (Tamhane).
3. Southern sector consisting of eight hot springs located at Khed, Unhavre (Khed), Aravli, Tural, Rajawadi, Sangameshwar, Math and Rajapur. Geochemistry of all the hot spring waters except Rajapur, are Alkali chloride type.

Rajapur hot spring water is bicarbonate type. Thermal waters have relatively high chloride content. The distinctly different range of chloride content of hot water suggests that occurrence and movement of thermal water is not connected with hydrologic cycle of surrounding cold water. Boron content except Unhavre (Khed), Khed (both 1 ppm), Rajapur, Math (both 0.5 ppm) hot springs is <0.5 ppm. Similarity of Cl/B ratio indicates that Math and Rajapur hot springs probably draw thermal water from reservoirs of similar hydrological condition. Cl/B value of Khed and Unhavre (Khed) hot springs suggest hydraulic continuity and their association with same geothermal system. Similar chloride and boron values form Tural-Rajwadi indicate their source in same geothermal system. Other hot springs having relatively high Cl/B ratio represent independent geothermal systems. Flourine values in thermal water of west coast are 1 to 3 ppm. It is similar to well-known geothermal fields at Ice land, USSR, and New Zealand. Lithium in thermal water at Unhavre (Tamhane), Vadavli, Pali, Ganeshpuri is <0.5 ppm. Lithium is more similar to thermal water in Basaltic province of Iceland. In other geothermal fields of the world, the lithium content is higher. Majority of geothermal systems in West coast have minimum reservoir temperature of the order of 120°C ± 10°C.

Twelve exploratory bore holes were drilled with depth ranging from 50 to 500 m in West coast areas. These included four bore holes at Ganeshpuri-Akloli, six at Unhavre (Khed), and two at Tural-Rajwadi. Studies carried out, so far, have shown that adequate supplies of hot water can become available by drilling shallow production wells at Unhavre khed, Tural-Rajwari and Ganeshpuri-Akloli and Sativli thermal spring areas.

Ganeshpuri hot springs are already attracting large numbers of tourists for hot water bath. Development of ‘Sauna baths’, animal husbandry, poultry farming, freshwater fish farming and greenhouse on a large scale for increase in the production of vegetables mushrooms under controlled conditions through multiple cropping can be thought of, which not only save the sizeable amount of fossil fuels but raise the economy of the Nation.

## 15.4 Conclusion

Almost all the 300 thermally anomalous areas have been examined. Thirty one areas have been studied in details, out of which, shallow drilling has been done only in 16 areas. Surface studies on Geology, Hydrogeology and Geochemistry (including isotope geochemistry) have been accomplished in all the areas. Subsurface studies based on geophysical exploration and shallow to intermediate drilling have been accomplished in all the areas. The deepest exploratory bore holes drilled are in Puga (385 m), Chhumathang (220 m), Manikaran (700 m), Tapoban (728 m), Tattapani (620 m) and West coast (500 m). Thermal discharges are at temperatures of 90–140°C in the promising areas. Thermal fluids issuing from the bore holes have limited output. Electrical power production of kWe level only is possible from the thermal discharges from the exploratory bore holes drilled so far. However, reservoir simulation studies have suggested the possibility of generating over 3 MWe electric power in Puga geothermal field if deeper levels are probed at least up to the depth of 500 m. Direct heat application on a moderate scale only, is possible from the thermal discharges available from the bore holes. Monitoring of some of the selected geothermal manifestations in northern part of India has been taken up systematically for geochemical studies since 2005. This will add to in synthesising the enormous geothermal data generated during the last three decades and will also help in deciding the future course of action for the development of geothermal prospects in the country.

# 16
## Biofuels: A review

### 16.1 Introduction

Oil provides energy for 95 per cent of transportation and the demand of transport fuel continues to rise. Biofuels are renewable liquid fuels coming from biological raw material and have been proved to be good substitutes for oil in the transportation sector. As such biofuels—ethanol and biodiesel are gaining worldwide acceptance as a solution to environmental problems, energy security, reducing imports, rural employment and improving agricultural economy.

Ethanol is used as fuel or as an oxygenate to gasoline. Raw material used for producing ethanol varies from sugar, cereals, sugar beet to molasses in India. Brazil uses ethanol as 100 per cent fuel in about 20 per cent of vehicles and 25 per cent blend with gasoline in the rest of the vehicles. USA uses 10 per cent ethanol-gasoline blends whereas a 5 per cent blend is used in Sweden. Australia uses 10 per cent ethanol-gasoline blend. Use of 5 per cent ethanol-gasoline blend is already approved by Bureau of Indian Standards (BIS) and is in progressive state of implementation in the country. BIS standards for 10 per cent blend need to be drafted after conducting trials and fixing parameters.

Biodiesel is made from virgin or used vegetable oils (both edible and non-edible) and animal fats through trans-esterification and is a diesel substitute and requires very little or no engine modifications up to 20 per cent blend and minor modification for higher percentage blends. The use of biodiesel results in substantial reduction of unburnt hydrocarbons, carbon monoxide and particulate matters. It has almost no sulphur, no aromatics and has about 10 per cent built in oxygen, which helps it to burn fully. Its higher cetane number improves the combustion.

Sunflower and rapeseed are the raw materials used in Europe whereas soyabean is used in USA. Thailand uses palm oil, Ireland uses frying oil and animal fats. It is proposed to use non-edible oil for making biodiesel.

### 16.2 Rationale of biofuels for transport in India

The rationale of taking up a major program for the production of biofuels for blending with gasoline and diesel in our country emanates from a variety of factors. First, there is no alternative to the petroleum-based fuels, i.e. motor spirit or gasoline and high speed diesel (HSD) for the transport sector which is the major consumer of petroleum products. Secondly, biofuels are environmentally superior fuels and their use becomes compelling if the prescribed emission norms are to be achieved. Thirdly, there is need to meet the global environmental concern about climate change, ensure energy security, reduce imports, generate employment for the poor and achieve a number of other objectives of the Tenth plan.

## 16.3 Automotive engines

Automobiles use two groups of engines, based on:

1. Constant pressure cycle which in practice is diesel engine and alternatively called compression ignition engine. The fuel for this kind of engine is diesel a major fraction of crude oil distillation. These are used for all our heavy vehicles in railway transport, in tractors, etc.
2. Constant volume cycle which in practice is our gas engines and alternatively called spark ignition engine. The fuel for this kind of engine is gasoline cut of the crude oil. These engines are used for all light vehicles like cars, three wheelers and two wheelers. Gasoline gives the advantage of making possible two stroke engines for motor bikes, scooters, etc. without the need of cumbersome valve mechanism. The advantages are in the form of quick start, fast acceleration, no large quantity of carbon emission, particulate matter (PM). Gasoline has high calorific value of 10,000 kcal/kg and all the desirable properties for storage, ignition, combustion and handling. The demand for light vehicles continues to grow faster than for heavy vehicles.

From environmental aspects, to achieve Bharat II emission standards, there are problems in using petrol and diesel as fuels. There are strong reasons why substitutes should be found and used for motor spirit/gasoline and diesel.

## 16.4 Gasoline (motor spirit) and its substitute—ethanol

### 16.4.1 Problems with gasoline

There are several problems in using gasoline or motor spirit or petrol which are derived from crude oil. Petroleum reserves are finite. Emissions from engines using gasoline or motor spirit such as nitrogen oxides, sulphur dioxide, carbon dioxide and particulate matter cause pollution. Gasoline has knocking tendency which limits the compression ratio of the gas engine. Tetraethyl lead (TEL) is an additive that improves the anti-knocking rating of the fuel dramatically. The harmful effect of the lead led to banning of its use. Benzene or cyclic compounds also increase the octane rating. Benzene is, however a known carcinogenic material. Alternatively, methyl tert-butyl ether (MTBE) and ethyl tert-butyl ether (ETBE) are used as additives to improve anti-knocking tendency and to reduce other vehicular emissions. The oxygenated fuels burn more completely and so reduce carbon monoxide emission up to 20 per cent.

## 16.4.2 Ethanol as an automotive fuel

The advantages of using ethanol and methanol as automotive fuels are that they are oxygenates containing 35 per cent oxygen and are renewable. They reduce vehicular emission of hydrocarbons and carbon monoxide and eliminate emission of lead, benzene, butadiene, etc. While the calorific value of ethanol is lower than that of gasoline by 40 per cent it makes up a part by increased efficiency. Blends below 10 per cent of ethanol do not present problems. However, blends above 20 per cent pose certain difficulties such as: (i) higher aldehyde emissions, (ii) corrosiveness, affecting metallic parts, (iii) higher latent heat of vaporisation causing startability problem, (iv) higher evaporation losses due to higher vapour pressure, and (v) requiring large fuel tank due to lower calorific value.

As there is a theoretical decrease in the energy content of gasoline blended with oxygenates, a decrease in mileage, km/l of fuel consumed is expected. But in urban use a significant increase in fuel efficiency has been reported. The higher latent heat of vaporisation of ethanol than gasoline is expected to cause startability problem. But blend up to 25 per cent ethanol in gasoline poses no problem. Ethanol is corrosive in nature, absorbs moisture readily and can affect metallic parts (ferrous/nonferrous). However with the 10 per cent ethanol blend no compatibility problems have been found. Standards for ethanol use as fuel blending have been prescribed.

## 16.4.3 Production of ethanol

### *Raw material*

Three classes of vegetative sources (raw materials) can be used:

1. Starch as grain, corn and tubers like cassava.
2. Sugar plants (sugar beet or sugar cane).
3. Cellulose plants (general tree and biomass).

## *Process*

Ethanol production is very ancient linked with making potable alcohol. The liquor containing corn, grapes juice, molasses, etc. are fermented by adding yeast to it in batch fermentators for a number of hours (minimum 40 hours) when fermentation gets completed it is distilled to remove water and undesirable compounds for achieving 99 per cent + purity.

*Through sugarcane:* Through sugarcane sugar route. The major source of ethanol production in the country is via sugarcane-sugar-molasses route. This provides better economy by sale of sugar; molasses becomes the byproduct of the sugar. Average sugar cane productivity in India is about 70 MT per hectare and ethanol produced from one MT of sugarcane is 70 litres.

*Through sugar beet:* In European countries sugar beet is preferred. Sugar beet has certain advantages over sugarcane. It provides higher yield (12.5 to 17.5 tons per hectare of sugar against 7.5 to 12 tons of sugar per hectare from sugarcane in addition to low requirement of water, lower maturity time and lower power requirement for crushing. Sugar beet cultivation and its processing to ethanol needs to be promoted in the country

*Starch-based alcohol production:* Alcohols are produced from a large number of different starch crops as barley, wheat, corn, potato, sorghum, etc. The conversion of starch into alcohol follows the same process of fermentation and distillation as that of sugarcane. Corn can provide about 275 litres of ethanol from one MT. With productivity of 2 MT per hectare, 550 litres of ethanol can be produced from one hectare of corn plantation. In addition to lower yield per hectare of ethanol, corn presents the problem of disposal of residue, but it can be used as animal feed. It can, however, be utilised for value added products which can provide starch-based alcohol production economical. Corn oil is edible and its use in India for production of ethanol is not economically feasible.

*Ethanol made from cellulosic biomass:* In the coming years it is believed that cellulosic biomass will be the largest source of bioethanol. The broad category of biomass for the production of ethanol includes agricultural crops and residues and wood. Biomass resources are abundant and have multiple application potential. Among the various competing processes, bioethanol from lignocellulosic biomass appears to have economic potential. The crops residues such as rice straw, bagasse, etc. are not currently used to derive desired economic and environmental benefits and thus they could be important resource base for bioethanol production. As for example one MT of rice straw or bagasse can give over 400 litres of ethanol.

Cellulosic materials are polymers of sugar and are difficult to decompose by enzymes and need breaking of bonds beforehand. Two different routes are being tried. One is by action of chemical (acid or new generation of enzymes) and the second is the thermal route of gasification. The first route is being generally followed as in paper pulp industry. However, for ethanol production economics are not favourable. The gasification route provides better economics but looks to be very complicated. It is as yet in an experimental stage.

### 16.4.4 Economics of production

The major factors that affect the ethanol cost are the following: the yield of sugarcane and cycle of production, the sugar contents in the juice, efficiency in juice extraction as well as in fermentation, and lastly utilisation of waste. Under the existing price structure, sugar production provides higher value addition than sugarcane to ethanol.

### 16.4.5 Utilisation of waste

Two major waste products are generated in the ethanol production from sugarcane namely, Bagasse that can be used as boiler fuel and also as raw material for news print and spent wash that can be used for generation of biogas which is a gaseous fuel of medium heating value.

### 16.4.6 Research areas in the field of bioethanol

Ethanol producers in the United States produce around 1.5 billion gallons of ethanol each year, mostly derived from corn. As demand for ethanol increases, other biomass resources, such as agricultural and forestry wastes, municipal solid wastes, industrial wastes, and crops grown solely for energy purposes, will be used to make ethanol. Research activities over the past 20 years have developed technology to convert these feedstock to ethanol.

Fuel ethanol is currently produced from the easily fermented sugar and starch in grain and food processing wastes. Soon, new technologies will be economically viable for converting plant fibre to ethanol. A portion of the agricultural and forestry residues (corn stover, stalks, leaves, branches) which are presently burned or left in the field may therefore be harvested for biofuel production. There will be many benefits by connecting the established corn ethanol industry with the emerging technologies that produce ethanol from agricultural wastes and other types of biomass.

Sweet sorghum can be grown in temperate and tropical regions. Sweet sorghum produces a very high yield in comparison with grains, sugar, lignocellulosic biomass (on average a total of 30 dry tons/ha per year). Plantations need less seed than for other crops: 15 kg/ha compared with 40 kg/ha for corn, or 150 kg/ha for wheat.

### 16.4.7 Meeting the ethanol demand for blending

The ethanol demand for blending can be calculated from the plan projection of the future growth in gasoline. The Indian government has taken the decision to make the 5 per cent blending in gasoline as mandatory in phased manner. The present production of ethanol is mainly from molasses. It is projected that in the year 2015, 1790 thousand kilolitre of ethanol from sugarcane directly will be produced in addition to 2300 thousand kilolitre from molasses. Thus for meeting the demand of ethanol for 10 per cent blending, capacity to produce ethanol in the country is sufficient.

But for blending purposes anhydrous ethanol is required and the distilleries will have to put up facility to dehydrate ethanol and produce anhydrous ethanol. For higher percentage of blending and till the demand becomes stable, correspondingly higher quantities of ethanol, and consequently more sugarcane and other raw material, would be needed. The target should be to raise the blending in stages to 10 per cent by the end of the tenth plan.

Bioethanol is an attractive fuel due to its renewable origin and its oxygen content, but it is unable to be used directly in diesel engines. Although biodiesel can be produced with bioethanol through ethanolisis, direct blending of ethanol and diesel fuel, called e-diesel, has at least the same potential to reduce particulate emissions, despite their much lower production cost. The main drawback is that ethanol is immiscible with diesel fuel over a wide range of temperatures, leading to phase separation. Consequently, in many cases the presence of a surfactant and co-solvent additive in the e-diesel blend becomes necessary.

#### *High blends bioethanol*

High bioethanol blends require dedicated vehicles, whereas low bioethanol blends do not. High blends contain a high proportion of bioethanol and effectively substitute fossil fuels. High blends can substantially reduce greenhouse gas emissions, depending on how they are produced. Due to the difference in properties between fossil fuels and bioethanol, high blends require some modifications to the vehicle engine and a dedicated fuelling infrastructure.

#### *Low blends bioethanol*

Low blends represent a quick way of introducing large volumes of biofuel into road transport fuels without making any alterations to fuel supply infrastructure or vehicles. Low blends are seen as a relatively cost-effective way of reducing fossil fuel consumption. Low blends using biofuels such as

bioethanol and biodiesel have been used in Europe since the early 1900s.
Recommendations on ethanol

1. The country must move towards the use of ethanol as substitute for motor spirit. Though it is technically feasible to design and run automobiles on 100 per cent ethanol, for the reason of its limited availability and compatibility with vehicles presently in use, blending of ethanol with motor spirit needs to make a very modest beginning to be raised to 10 per cent, as capacity to produce anhydrous ethanol is built up.
2. Ethanol may be manufactured using molasses as the raw material. The industry should be encouraged to supplement the production of alcohol from molasses by producing alcohol from sugarcane juice directly in areas where sugarcane is surplus. For this purpose restrictions on movement of molasses and putting up ethanol manufacturing plants may be removed.
3. Imported ethanol should be subject to suitable duties so that domestically produced ethanol is not costlier than the imported one.
4. Ethanol diesel blending requires emulsifier and also poses certain storage and technical problems. Indian Institute of petroleum is working on the subject. Ethanol diesel blending should await the solution of the problems.
5. Buyback arrangement with oil companies for the uptake of anhydrous alcohol should be made.
6. To reduce cost of production of ethanol, the following measures may be considered:
   (a) Provision of incentives for new economic sized distilleries incorporating state of art technology such as, molecular sieve technology for making anhydrous alcohol.
   (b) Integration of distillery with sugar plant to have multiple choice of making sugar or direct sugarcane to ethanol.
   (c) Economics of ethanol production from other feedstock such as sugar beet, corn, potatoes, grain, straw, etc. should be studied. R&D should be carried out to develop technologies which are competitive in cost of production of ethanol from molasses.

## 16.5 Biodiesel

### 16.5.1 Problems in using petroleum-derived HSD

Like all fossil fuels the use of HSD also makes net addition of carbon to the atmosphere. In addition, diesel emits particulate matter (PM), especially below micron 2.5 which passes the protection system of the body to get lodged in lungs causing reduction in its vital capacity. In association with the particulate matter the unburnt oil is carcinogenic. In addition carbon monoxide, hydrocarbon, sulphur and PAH emissions are on the higher side. Attempts to reduce particulate matter emissions have not been entirely successful. A 15 per cent ethanol—diesel blend reduces particulate matter emission, however the blend provides certain technical problems for which satisfactory solution has not been found. These have been discussed in the succeeding paragraphs.

### 16.5.2 Characteristics of biodiesel

Biodiesel is fatty acid ethyl or methyl ester and has properties similar to petroleum diesel fuels. Similar to the HSD, biodiesel is its substitute. The specifications of biodiesel are such that it can be mixed with any diesel fuel. Cetane number (CN) of the biodiesel is in the range of 48–60 and the sulphur content is typically less than 15 ppm. Studies conducted with biodiesel on engines have shown substantial reduction in particulate matter (25–50 per cent). However, a marginal increase in $NO_x$ (1–6 per cent) is also reported; but it can be taken care of either by optimisation of engine parts or by using De-$NO_x$ catalyst. HC and CO emissions were also reported to be lower. Non-regulated emissions like PAH, etc. were also found to be lower. Thus, biodiesel can supplement the supply of environment friendly fuels in our country in future. In conventional diesel fuels, the reduction in sulphur content is compensated by adding additive for lubricity of fuel injection pump (FIP). Biodiesel is reported to have superior lubricity. Flash point of biodiesel is high (>100°C).

Its blending with diesel fuel can be utilised to increase the flash point of diesel particularly in India where flash point is 35°C well below the world average of 55°C. This is important from the safety point of view. The viscosity of biodiesel is higher (1.9 to 6.0 cSt) and is reported to result into gum formation on injector, cylinder liner, etc. However, blends of up to 20 per cent should not give any problem. While an engine can be designed for 100 per cent biodiesel use, the existing engines can use 20 per cent biodiesel blend without any modification and reduction in torque output. In USA, 20 per cent biodiesel blend is being used, while in European countries 5–15 per cent blends have been adopted.

Biodiesel can be blended in any ratio with petroleum diesel fuel. It can be stored just like the petroleum diesel fuel and hence does not require separate infrastructure. Biodiesel has been accepted as clean alternative fuel by USA. Due to its favourable properties, biodiesel can be used as fuel for diesel engines (as either, B5-a blend of 5 per cent biodiesel in petro-diesel fuel or B20 or B100). USA uses B20 and B100 biodiesel, France uses B5 as mandatory in all diesel fuel.

Sunflower, rapeseed is the raw material for biodiesel used in Europe whereas soyabean is used in USA. Thailand uses palm oil, Ireland uses frying oil and animal fats. In India it is proposed to use non-edible oil for producing biodiesel. Presently many species are being grown which yield seed containing non-edible oil. The present production is being used and much surplus is not available. It is proposed to take up a major plantation program of *Jatropha curcas*, for reasons which are given in the later part of this chapter, to provide the oil needed.

### 16.5.3 Rationale

The rationale of taking up a major program for the production of biodiesel in India for blending with diesel lies in the context of:

1. Biodiesel being a superior fuel than HSD from the environmental point of view.
2. Use of biodiesel becomes compelling in view of the tightening of automotive vehicle emission standards and court interventions.
3. The need to provide energy security, especially for the rural areas.
4. The need to create employment.
5. Providing nutrients to soil, checking soil erosion and land degradation.
6. Rehabilitating degraded lands through greening.
7. Addressing global concern relating to containing carbon emissions as provided in the framework convention on climate change.
8. Reduce dependence on crude oil imports.

### 16.5.4 Feasibility of producing biodiesel as petro-diesel substitute

For the reason of edible oil demand being higher than its domestic production, there is no possibility of diverting this oil for production of biodiesel. There are many tree species which bear seeds rich in oil. Of these some promising tree species have been evaluated and it has been found that there are a number of them such as *Jatropha curcas* and *Pongamia pinnata* (Honge or Karanja) which would be very suitable in our conditions. However, *Jatropha curcas* has been found most suitable for the purpose. It can be planted on under-stocked forest lands managed by the J.F.M.

Committees, farmers field boundaries to provide protective hedge, fallow lands, on farmers' holdings as agroforestry along with agricultural crops, public lands along railway tracks, highways, canals and community and government lands in villages. It can also be planted under the poverty alleviation programs that deal with land improvement.

### 16.5.5 Economics of biodiesel from Jatropha curcas

The byproducts of biodiesel from *Jatropha* seed are the oil cake and glycerol which have good commercial value. These by-products shall reduce the cost of biodiesel depending upon the price which these products can fetch. The cost components of biodiesel are the price of seed, seed collection and oil extraction, oil trans-esterification, transport of seed and oil. The cost of biodiesel produced by trans-esterification of oil obtained from *Jatropha curcas* seeds will be very close to the cost of seed required to produce the quantity of biodiesel as the cost of extraction of oil and its processing in to biodiesel is recoverable to a great extent from the income of oil cake and glycerol which are by-products.

Taking these elements into account, the price of biodiesel has been worked out assuming cost of seed as Rs. 5 per kg, 3.28 kg of seed giving one litre of oil and varying prices of by-products. The cost of biodiesel varies between Rs. 16.59 to 14.98 per litre if the price of glycerol varies between Rs. 60 and 40 per kg.

### 16.5.6 Potential availability of land for Jatropha plantation

With appropriate extension and availability of planting material it should be easy to cover 13.4 million hectare of land with Jatropha curcas as indicated below:

1. Forests cover 69 million hectares of which 38 million hectare is dense forest and so 31 million hectare is under-stocked. Of this 14 million hectare of forests are under the Scheme of Joint Forestry Management. Three million hectare (notional) of land in forests should easily come under *Jatropha curcas* plantation.
2. One hundred and forty two million hectare of land is under agriculture. It will be reasonable to assume that farmers will like to put a hedge around 30 million hectare of their fields for protection of their crops. It will amount to 3.0 million hectare (notional) of plantation.
3. The cultivators are expected to adopt it by way of agroforestry. Considerable land is held by absentee landlords who will be attracted to *Jatropha curcas* as it does not require looking after and gives a net income of Rs. 15,000 per hectare. Two million hectare of notional plantation is expected.
4. Culturable fallow lands are reported to be 24 million hectare of which current fallow lands are 10 million ha and other fallows are 14 million

hectare. Ten per cent of such land ( 2.4 million hectare) is expected to come under *Jatropha curcas* plantation.

5. On wastelands under Integrated Watershed Development and other poverty alleviation programs of Ministry of Rural Development a potential of 2 million hectare of plantation is assessed.
6. On vast stretches of public lands along railway tracks, roads and canals. One million hectare of notional coverage with *Jatropha curcas* is a reasonable assessment.

In addition about four million hectare of wastelands could also be brought under such plantation.

### 16.5.7 Specifications and quality standards for biofuels

ASTM has issued biodiesel standard D 6751 in December 2001, which covers the use of pure biodiesel (B100) into conventional diesel fuel up to 20 per cent by volume (B20). This replaces the provisional specification PS 121 issued in 1999. Austria (ON C 1191), France (JO), Italy (UNI 10635) and Germany (DIN E 51606) had issued biodiesel standards in 1997, Sweden in 1996 and a common draft standard EN 14214 for the European Union has also been announced. The new Italian biodiesel standard, which will replace UNI 10,635, has been finalised and will be released soon.

The standards for biodiesel in India are under formulation and are proposed to be based on standards adopted by European Union. It is necessary that the approval of vehicle, engine and fuel injection manufactures is taken before finalising standards and implementing fuel change. By getting warranties from OEMs and FIE manufacturers, the customer acceptance of biofuels will increase and shall go a long way in enhancing the use of biofuels.

### 16.5.8 R&D issues needing attention

#### *Raw material (Jatropha seed and oil)*

Selection of improved germ-plasm material for quality and quantity of oil; selection of the biocrop for production of biodiesel, i.e. Jatropha curcas and others; developing agro-technologies for different agro-climatic regions; total chemical analysis of all potential non-edible oils with special reference to Jatropha curcas oil.

#### *Production technology*

Research efforts for perfecting an efficient chemical/catalyst conversion process; development of biocatalyst, i.e. lipase catalysed esterification;

development of heterogeneous catalyst, i.e. use of smart polymers; alternate uses of by-products, i.e. glycerol and meal cake.

### *Utilisation as fuel*

Data generation and production of biodiesel from all possible feed stocks; response of different available additives and their dosages on the biodiesel; effect of biodiesel on elastomers, corrosion, etc. stability of biodiesel—oxidation stability, thermal stability and storage stability; engine performance and emissions based on different feedstock-based biodiesels; toxicological studies and tests to check adulteration.

### *Plants in operation/under construction*

Different technologies are currently available and used in the industrial production of biodiesel, which is sold under different trademarks. For example, there are the Italian processes Novamont, and the French IFP. A number of units are manufacturing biodiesel worldwide. These units are using sunflower oil, soyabean oil, rapeseed oil, used-frying oil, *Jatropha* oil, etc. as a source of triglycerides. Out of 85 plants identified, 44 plants were in Western Europe with Italy as the leading country with 11 plants, 29 plants in Eastern Europe, 8 plants in North America and 4 plants in the rest of the world. Overall capacity grew from 1,11,000 tons in 1997 to 19,86,000 in 2006. USA is the fastest growing newcomer and a number of companies are emerging there. Additional capacities are expected in Japan and the palm oil producing countries, Indonesia and Malaysia. Actual production grew from 25,000 tons in 1997 to 9,61,000 tons in 2006. France is the leading producer with 3,27,000 tons (in 2006).

### *Blending of esters and diesel*

Blending conventional diesel fuel (DF) with esters (usually methyl esters) of vegetable oils is presently the most common form of biodiesel. The most common ratio is 80 per cent conventional diesel fuel and 20 per cent vegetable oil ester, also termed ‘B20’, indicating the 20 per cent level of biodiesel; There have been numerous reports that significant emission reductions are achieved with these blends and no engine problems were reported in larger-scale tests with B20. Another advantage of biodiesel blends is the simplicity of fuel preparation, which only requires mixing of the components. Ester blends have been reported to be stable. One limitation to the use of biodiesel is its tendency to crystallise at low temperatures below 0°C, causing problems in fuel pumping and engine operation. One solution to this problem may be the use of branched-chain esters, such as isopropyl esters. Another method to improve the cold flow properties of vegetable oil esters is to remove high-melting saturated esters by inducing crystallisation with cooling, a process known as winterisation.

## *Storage and handling of biodiesel*

As a general rule blends of biodiesel and petroleum diesel should be treated like petroleum diesel. Though the flash point of biodiesel is high, still storage precautions somewhat like that in storing the diesel fuel need to be taken. Based on experience so far, it is recommended that biodiesel can be stored up to a maximum period of 6 months. Biodiesel vegetable methyl esters contain no volatile organic compounds that can give rise to poisonous or noxious fumes. There is no aromatic hydrocarbon (benzene, toluene, xylene) or chlorinated hydrocarbons. There is no lead or sulphur to react and release any harmful or corrosive gases. However, in case of biodiesel blends significant fumes released by benzene and other aromatics present in the base diesel fuel can continue.

## *Engine development and modifications*

The use of unrefined vegetable oil leads to poor fuel atomisation due to high viscosity resulting in poor combustion and also more gum formation in fuel injector, liner, etc. The results of emissions of using unrefined vegetable oils were unfavourable and were also accompanied by deposit formation . Therefore, it is necessary to esterify the vegetable oil for use in engines. However, these problems can be addressed by use of a suitable additives package. Engine oil dilution is a potential problem with biodiesel since it is more prone to oxidation and polymerisation than diesel fuel. The presence of biodiesel in engine could cause thick sludge to occur with the consequence that the oil becomes too thick to pump. Engine oil formulations need to be studied to minimise the effect of dilution with biodiesel. It must be noted that the light duty diesel engines are sufficiently different from heavy duty diesel engines in many aspects and one should not expect that the emission behaviour of the two types of engines would be same. This fact should be kept in mind while transferring conclusions of studies done on one type of engine to other type of engines.

## *Marketing and trade*

Biodiesel mixes easily in any proportion with the conventional diesel and by virtue of its high density it can be easily blended in a tank containing petroleum diesel. Its handling and storage is just like the petroleum diesel and no separate infrastructure is required. Therefore, the blending of biodiesel, which is transported by tankers, should be carried out at depots of diesel marketing and distribution companies. The biodiesel blends do not need separate dispensing and existing diesel dispensing station can also dispense biodiesel blends. Since the percentage of biodiesel to be blended will have to start from a low level, say 5 per cent, and gradually increase, studies related to blending will need to be carried out. The role of marketing companies in distribution, pricing, taxation, interstate movement and the direct and indirect impact of biodiesel, e.g. employment generation, balance of trade, emission benefits, etc. need to be studied.

### *R&D work done in India*

In India, attempts are being made for using non-edible and under-exploited oils for production of esters. Punjab Agricultural University is actively involved in R&D work on plant oils and their esters (biodiesel) as alternate fuel for diesel engines since early eighties. Indian Institute of Petroleum (IIP) is actively pursuing the utilisation of non-edible oils for the production of biodiesel, additives for lubricating oils, saturated and unsaturated alcohols and fatty acids and many other value added products. Indian Institute of Chemical Technology extracted oil from *Jatropha curcas*. A catalyst-free process (Indian Patent filed, US Patent being filed) that is insensitive to moisture or high FFA content has been developed at IICT, and an oil of any FFA content can be converted to the alkyl ester. Besides, preliminary studies on the utilisation of non-edible oils such as Neem, Mahua, Linseed, etc. as fuel are being carried out at IIT, Delhi and IIT, Madras. IOC R&D is also doing some work on the *trans*-esterification of vegetable oils. IOC (R&D) has already set up a biodiesel production facility of 60 kg/day at Faridabad. Mahindra & Mahindra, Ltd. has a pilot plant utilising Karanj for biodiesel production and has carried out successful trials on tractors using this fuel.

## 16.6 Biofuel for transport

Oil provides energy for 95 per cent of transportation and the demand of transport fuel continues to rise. The extract from the third assessment report of the IPCC to climate change provides the most accepted forecast on the subject. According to this assessment global oil demand will rise by about 1.6 per cent from 75 mb/d in the year 2000 to 120 mb/d in 2030. Almost three quarters of the increase in demand will be from the transport sector. Oil will remain the fuel of choice in road, sea and air transportation. Our country being a developing country, the increase in demand in our country for oil for use in the transport sector will grow at a much higher rate. All countries including India are grappling with the problem of meeting the ever increasing demand of transport fuel within the constraints of international commitments, legal requirements, environmental concerns and limited resources. In this connection transport fuels of biological origin have drawn a great deal of attention during the last two decades.

Biofuels are renewable liquid fuels coming from biological raw material and have been proved to be good substitutes for oil in the transportation sector. As such biofuels—ethanol and biodiesel are gaining worldwide acceptance as a solution for problems of environmental degradation, energy security, restricting imports, rural employment and agricultural economy.

Ethanol is used as fuel or as an oxygenate to gasoline. Raw material used for producing ethanol varies from sugar in Brazil, cereals in USA, sugar beet in Europe to molasses in India. Brazil uses ethanol as 100 per cent fuel in about 20 per cent of vehicles and 25 per cent blend with gasoline in the rest of the vehicles. USA uses 10 per cent ethanol-gasoline blends whereas a 5 per cent blend is used in Sweden. Australia uses 10 per cent ethanol-gasoline blend. Use of 5 per cent ethanol-gasoline blend is already approved by BIS and is in progressive state of implementation in the country. BIS standards for 10 per cent blend need to be drafted after conducting trials and fixing parameters.

Biodiesel is ethyl or methyl ester of fatty acid. Biodiesel is made from virgin or used vegetable oils (both edible and non-edible) and animal fats through transesterification. Just like petroleum diesel, biodiesel operates in compression ignition engine; which essentially require very little or no engine modifications up to 20 per cent blend and minor modification for higher percentage blends because biodiesel has properties similar to petroleum diesel fuel. Biodiesel can be blended in any ratio with petroleum diesel fuel. It can be stored just like the petroleum diesel fuel and hence does not require separate infrastructure. The use of biodiesel in conventional diesel engines results in substantial reduction of unburnt hydrocarbons, carbon monoxide and particulate matters. Biodiesel is considered clean fuel since it has almost no sulphur, no aromatics and has about 10 per cent built in oxygen, which helps it to burn fully. Its higher cetane number improves the combustion even when blended in the petroleum diesel. Biodiesel has been accepted as clean alternative fuel by USA and its production presently is about 100 million Gallons. Each State has passed specific bills to promote the use of biodiesel by reduction of taxes. Sunflower and rapeseed are the raw materials used in Europe whereas soyabean is used in USA. Thailand uses palm oil, Ireland uses frying oil and animal fats. Due to its favourable properties, biodiesel can be used as fuel for diesel engines (as either, B5-a blend of 5 per cent biodiesel high speed diesel) or B20 or B100). USA uses B20 and B100 biodiesel, France uses B5 as mandatory is all diesel fuel. It can also be used as an additive to achieve the following objectives:

1. To reduce the overall sulphur content of blend (refineries can meet, to some extent, the requirement of low sulphur diesel fuel).
2. To compensate for lubricity loss due to sulphur removal from diesel fuel.
3. To enhance the cetane number of diesel fuel (North–East refineries can greatly benefit by meeting the cetane requirement).

### 16.6.1 Engine development and modification

Need for engine development and modification have been felt in case of higher blends and that of diesel-ethanol emulsions which pose certain technical problems. Corrosion of fuel inaction system by use of ethanol/biodiesel in higher blends calls for study and coordination with vehicle manufacturers.

## 16.7 Challenges and possible approaches for integration of biofuels into refineries

The future widespread use of biofuels depends on solving multiple issues such as:

1. Identifying a large, consistent quantity of renewable feedstock.
2. Producing biofuels, cost competitive with other fuels.
3. Building an efficient supply chain for collection, storage and transportation of the bio-based feedstock, intermediates such as expelled oils, and derived fuel or blending components.
4. Developing new chemical process technology to produce fuels from the unique and often variable composition of these highly oxygenated feedstock.
5. Producing biofuels compatible with the existing transportation and fuel infrastructure.
6. Ensuring that the government policies formulated are technology neutral to enable the development and introduction of improved and higher quality biofuels.

Many profitable processing options exist for integrating biorenewable feeds and fuels into existing refineries by successfully addressing these issues, including the production of liquid transport fuels through co-processing and by use of modular production plants.

Figure 16.1 schematically depicts several options for biofuel production from various biomass sources. Some of the routes are already in commercial practice, such as ethanol from the fermentation of corn or sugar cane or fatty acid methyl ester (FAME) from rapeseed oil. Others, such as the deoxygenation of plant oils to produce a ‘green diesel’ hydrocarbon fuel, are currently entering the market.

Refineries are being driven by market conditions to process more complex and heavier feedstock, and to respond to a variety of regulatory requirements such as greenhouse gas emissions and transport fuel standards. Yet, refineries must remain competitive through use of energy-efficient processes that deliver optimal yields of the desired product mix at reasonable throughput. This can be achieved by developing and implementing technologies derived through a deep understanding of feedstock, processing and catalysis, engaging with refiners as strategic partners rather than as tactical customers, and systematically exploring the integration of emerging options such as biofuels in a manner compatible with already available infrastructure.

## 16.8 Future of biorefineries

There have been a lot of water cooler discussions and editorials about bioethanol and chemicals from agro-based products. The US is also giving a lot of lip service to this concept. How exactly does it unfold and what it means for the chemical industry, is the topic of discussion.

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass (Fig. 16.2). The biorefinery concept is analogous to today’s petroleum refineries, which produce multiple fuels and products from petroleum. Industrial biorefineries have been identified as the most promising route to the creation of a new domestic bio-based industry. By producing multiple products, a biorefinery can take advantage of the differences in biomass components and intermediates and maximise the value derived from the biomass feedstock.

A biorefinery might, for example, produce one or several low-volume, but high-value, chemical products and a low-value, but high-volume liquid transportation fuel, while generating electricity and process heat for its own use and perhaps enough for sale of electricity. The high-value products enhance profitability, the high-volume fuel helps meet national energy needs, and the power production reduces costs and avoids greenhouse gas emissions.

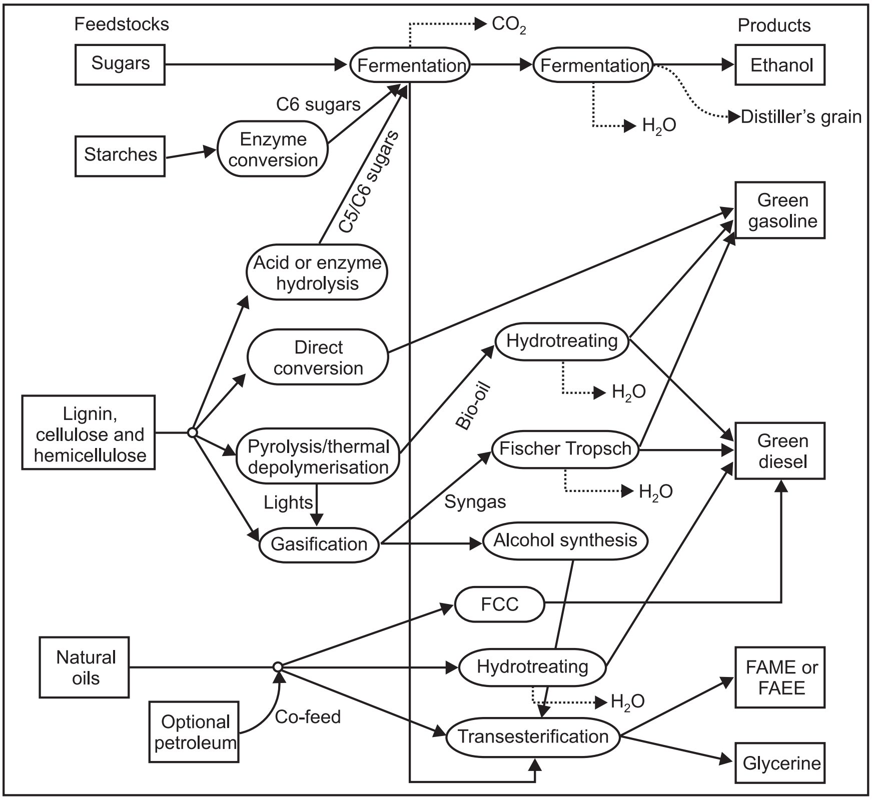



**Figure 16.1** Overview of biofuel production

## 16.8.1 Conceptual biorefinery

The National Renewable Energy Lab (NREL) is one of the premier laboratory funded by the US federal government, whose main objective is to find economic ways to generate bioethanol.

NREL's biorefinery concept is built on two different 'platforms' to promote different product slates.

1. The 'sugar platform' is based on biochemical conversion processes and focuses on the fermentation of sugars extracted from biomass feedstock.
2. The 'syngas platform' is based on thermochemical conversion processes and focuses on the gasification of biomass feedstock and by-products from conversion processes.

The NREL Biomass Program is involved with six major biorefinery development projects that are focused on new technologies for integrating the production of biomass-derived fuels and other products in a single facility.

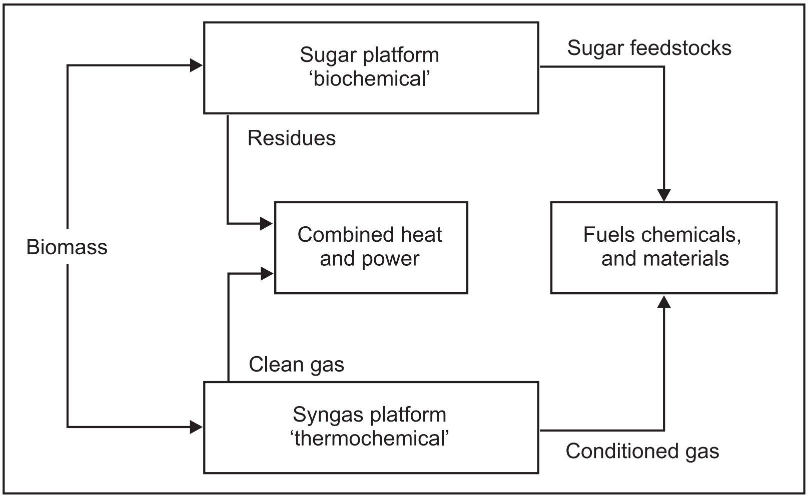



**Figure 16.2** Biorefinery concepts

The emphasis is on using new or improved processes to derive products such as ethanol, 1,3-propanediol, polylactic acid, isosorbide, and various other chemicals.

1. Second Generation Dry Mill Refinery (Broin and Associates, Inc.). This project will enhance the economics of existing ethanol dry mills by increasing ethanol yields and creating additional co-products.
2. Integrated Corn-based Biorefinery (E.I. duPont de Nemours & Co., Inc.). This project will build a bio-based production facility to convert corn and stover into fermentable sugars for production of value-added chemicals.
3. Making Industrial Biorefining Happen (Cargill Dow LLC National). This project will develop and validate process technology and sustainable agricultural systems to economically produce sugars and chemicals such as lactic acid and ethanol.
4. Advanced Biorefining of Distiller's Grain and Corn Stover Blends (High Plains Corp.). This project will develop a novel biomass technology to utilise distiller's grain and corn stover blends to achieve significantly higher ethanol yields, while maintaining the protein feed value.
5. MBI/USDA (John Ashworth).

## 16.8.2 Thermochemical process R&D

NREL's researchers have investigated the thermochemical conversion of renewable energy feedstock since the laboratories inception. Researchers have focused on developing gasification and pyrolysis processes for converting biomass and its residues to fuels, chemicals, and power.

Gasification R&D is working to produce bio-syngas with characteristics suitable for commercial applications. One major part of this effort is the development of biomass gasification combined cycles. Integrated biomass gasification with combined cycles can be used to generate synthesis gas that can be burned in gas turbines or used in fuel cells to produce electricity at high efficiency. The methods developed by NREL researchers for analysing, cleaning, and conditioning product gas to meet primemover (e.g. spark-ignited internal combustion engines, turbines, etc.) requirements are critical to making this technology commercially viable.

Fundamental work is also being conducted at NREL that provides a solid understanding of the chemistry of biomass pyrolysis, including stabilisation and upgrading of bio-oil, the potential applications of pyrolysis liquids, and the requirements for engineering systems that can produce fuels and chemicals via biomass pyrolysis on a large scale.

### 16.8.3 Life-cycle assessment

Life-cycle assessment (LCA) is an analytic method for identifying, evaluating, and minimising the environmental impacts of emissions and resource depletion associated with a specific process. When such an assessment is performed in conjunction with a techno-economic feasibility study, the total economic and environmental benefits and drawbacks of a process can be quantified.

Material and energy balances are used to quantify the emissions, resource depletion, and energy consumption of all processes, including raw material extraction, processing, and final disposal of products and by-products, required to make the process of interest operate. The results of this inventory are then used to evaluate the environmental impacts of the process so efforts can focus on mitigation. In India, detailed LCA studies need to be conducted on such systems.

### 16.8.4 Emerging technologies

PureVision is a new biorefinery company claiming to have a fractionation process that is an emerging platform technology that will economically convert diverse biomass into sugars, fibres, fuels, energy and industrial products. The company’s core technology (biomass fractionation) is a unique chemical and mechanical process of separating the major components of biomass and converting these separated biomass elements into value-added products. Once biomass is processed utilising PureVision’s fractionation technology, the separated components become raw materials for producing a wide range of products in biorefineries for many industries.

This advanced process is analogous to a computer's operating system, providing the principal technology platform for numerous applications. PureVision's technology platform encompasses many diverse industries. Industries that will benefit from economical biomass processing include:

1. Wood processors, including forest management
2. Waste management and resource recovery
3. Agriculture
4. Food processors
5. Biotechnology companies
6. Pulp, paper and fibre users and manufacturers
7. Petroleum and fuel suppliers, speciality chemical manufacturers, pharmaceutical companies
8. Electrical generators

Another emerging company, Iogen (www.iogen.ca), funded by Shell Technology Ventures, is struggling with making cellulosic ethanol commercially viable. Iogen claims to be a world leading biotechnology firm specialising in cellulose ethanol—a fully renewable, advanced biofuel that can be used in today's cars. Iogen also develops, manufactures and markets enzymes used to modify and improve the processing of natural fibres within the textile, animal feed, and pulp and paper industries.

### 16.8.5 Biomass feedstock

The renewable resource base of the United States and the world is currently underutilised, as biomass wastes from forest residues and food processing are often seen as a problem, rather than an opportunity. Renewable resources generated by the domestic agricultural and forestry industries have the potential to meet many market demands that are currently being filled by imported oil. Biomass, or plant matter, is made up of three major components: cellulose, hemicellulose and lignin. Biomass feedstock that can be utilised in the PureVision process include:

1. Agricultural crop residues (wheat straw, corn stover and sugarcane bagasse)
2. Small diameter trees and forest thinning
3. Energy crops (switchgrass, hybrid poplar, willow, etc.)
4. Other wastes including organics and paper from municipal solid waste and paper mill and municipal sewage sledges

Together, there are an estimated 500 MT of these biomass materials available annually in the US. If all 500 MT were converted to ethanol, approximately 33 billion gallons would be produced annually, equalling 30 per cent of the total liquid fuel consumed by the US transportation sector. However some worry about degradation of the soil over the years along with reduction of fertile land.

### 16.8.6 Abengoa biomass ethanol technology

The first commercial-scale Abengoa-based biomass plant is currently being constructed by Abengoa Bioenergy to demonstrate its biomass-to-ethanol process technology. Construction began in August of 2005. The biomass plant is located at the new BCyL Cereal Ethanol Plant in Babilafuente (Salamanca), Spain. Commissioning is expected to start by the end of 2006. The plant will process 70 tons of agricultural residues, such as wheat straw, each day and produce over 5 million litres of fuel grade ethanol per year. The commercial demonstration of the biomass to ethanol production technology marks an important milestone for the growth of Abengoa bioenergy in ethanol production from renewable resources (Fig. 16.3).

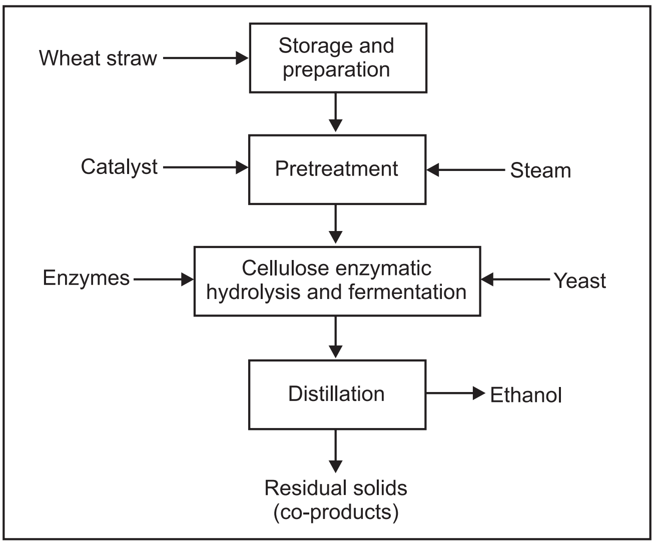



**Figure 16.3** Process block flow diagram of the BCyL biomass ethanol plant

The ultimate objective is to develop biomass ethanol technologies that are economically competitive with gasoline. Considering the rapid rise in the price of petroleum products, the need for developing alternative technologies for the production of fuel and chemicals from renewable resources such as agricultural residues (e.g. straw, corn stover, etc.) becomes more urgent.

The goals for the biomass plant are to commercially demonstrate the biomass to ethanol process, optimise plant operations, and establish a baseline for the future expansion of the ethanol industry. In addition to ethanol, the plant will generate sufficient amounts of fermentation residues for the development and testing of co-products, such as feed and chemicals.

The major processing steps of the plant include:

1. Feedstock storage and preparation
2. Pre-treatment
3. Cellulose hydrolysis
4. Ethanol fermentation
5. Ethanol recovery

The biomass feedstock, such as wheat or barley straw, is first milled and cleaned in the preparation stage and then pre-treated. The pre-treated biomass is digested by enzymes to release sugars, which will be further fermented by yeast to ethanol and carbon dioxide. Ethanol is recovered in the distillation process, and the fermentation residue is processed further as animal feed or to recover useful chemicals.

The company expects to implement the second phase of this project in the fall of 2010. In this phase, processed biomass will undergo fractionation, a technology currently under development, to extract lignin, pentose sugars, and manufacture feed products.

However, a corn-based ethanol has only slight benefits over traditional gasoline. The reason being that production of ethanol from corn requires significant consumption of energy. The study also stated that cellulosic ethanol offered significant benefits over gasoline.

The market for cellulosic ethanol is still emerging. While India and other countries are aggressively going after such projects, there is still a big lacuna in the process engineering and design aspects of such projects. There is a need to use advanced tools to optimise and accurately design such systems, so that they become commercially viable. Software vendors are busy sharpening their market offerings to address such design issues. The US Government through its national laboratories is taking steps in that direction. One such body is Center for Technology Transfer for Wisconsin (CTT) (www.cttinc.org). The other one is NREL (www.nrel.gov). The US Department of Energy offers a wealth of information on such projects.

# 17
# Biogas

## 17.1 Introduction

Biogas typically refers to a gas produced by the biological breakdown of organic matter in the absence of oxygen. Biogas originates from biogenic material and is a type of biofuel. Biogas is produced by anaerobic digestion or fermentation of biodegradable materials such as biomass, manure, sewage, municipal waste, green waste, plant material and energy crops. This type of biogas comprises primarily methane and carbon dioxide. Another type of gas generated by use of biomass is wood gas, which is created by gasification of wood or other biomass. This type of gas is also comprised primarily of nitrogen, hydrogen, and carbon monoxide, with trace amounts of methane.

The gases methane, hydrogen and carbon monoxide can be combusted or oxidised with oxygen. Air contains 21 per cent oxygen. This energy release allows biogas to be used as a fuel. Biogas can be used as a low-cost fuel in any country for any heating purpose, such as cooking. It can also be used in modern waste management facilities where it can be used to run any type of heat engine, to generate either mechanical or electrical power.

Biogas can be compressed, much like natural gas, and used to power motor vehicles and in the UK for example is estimated to have the potential to replace around 17 per cent of vehicle fuel. Biogas is a renewable fuel, so it qualifies for renewable energy subsidies in some parts of the world.

## 17.2 Production of biogas

Biogas is practically produced as landfill gas (LFG) or digester gas. A biogas plant is the name often given to an anaerobic digester that treats farm wastes or energy crops. Biogas can be produced utilising anaerobic digesters. These plants can be fed with energy crops such as maize silage or biodegradable wastes including sewage sludge and food waste. During the process, an air-tight tank transforms biomass waste into methane producing renewable energy that can be used for heating, electricity, and many other operations that use any variation of an internal combustion engine, such as GE Jenbacher gas engines. There are two key processes: Mesophilic and Thermophilic digestion.

Landfill gas is produced by wet organic waste decomposing under anaerobic conditions in a landfill. The waste is covered and mechanically compressed by the weight of the material that is deposited from above. This material prevents oxygen exposure thus allowing anaerobic microbes to thrive. This gas builds up and is slowly released into the atmosphere if the landfill site has not been engineered to capture the gas. Landfill gas is hazardous for three key reasons. Landfill gas becomes explosive when it escapes from the landfill and mixes with oxygen. The lower explosive limit is 5 per cent methane and the upper explosive limit is 15 per cent methane. The methane contained within biogas is 20 times more potent as a greenhouse gas than carbon dioxide. Therefore uncontained landfill gas which escapes into the atmosphere may significantly contribute to the effects of global warming. In addition landfill gas impact in global warming, volatile organic compounds (VOCs) contained within landfill gas contribute to the formation of photochemical smog.

### 17.2.1 Composition

The composition of biogas varies, depending upon the origin of the anaerobic digestion process. Landfill gas typically has methane concentrations around 50 per cent. Advanced waste treatment technologies can produce biogas with 55–75 per cent $CH_4$ or higher using in situ purification techniques. As produced, biogas also contains water vapour, with the fractional water vapour volume a function of biogas temperature, correction of measured volume for water vapour content and thermal expansion is easily done via algorithm. In some cases biogas contains siloxanes. These siloxanes are formed from the anaerobic decomposition of materials commonly found in soaps and detergents. During combustion of biogas containing siloxanes, silicon is released and can combine with free oxygen or various other elements in the combustion gas. Deposits are formed containing mostly silica ($SiO_2$) or silicates ($Si_xO_y$) and can also contain calcium, sulphur, zinc, phosphorus. Such white mineral deposits accumulate to a surface thickness of several millimetres and must be removed by chemical or mechanical means. Practical and cost-effective technologies to remove siloxanes and other biogas contaminants are currently available.

### 17.2.2 Applications

Biogas can be utilised for electricity production on sewage works, in a CHP gas engine, where the waste heat from the engine is conveniently used for heating the digester, cooking, space heating, water heating, and process heating. If compressed, it can replace compressed natural gas for use in vehicles, where it can fuel an internal combustion engine or fuel cells and is a much more effective displacer of carbon dioxide than the normal use in on-site CHP plants. Methane within biogas can be concentrated via a biogas upgrader to the same standards as fossil natural gas biomethane. If the local gas network allows for this, the producer of the biogas may utilise the local gas distribution networks. Gas must be very clean to reach pipeline quality, and must be of the correct composition for the local distribution network to accept. Carbon dioxide, water, hydrogen sulphide and particulates must be removed if present. If concentrated and compressed it can also be used in vehicle transportation. Compressed biogas is becoming widely used in Sweden, Switzerland, and Germany. A biogas-powered train has been in service in Sweden since 2005.

Various forms of biomass resources exist (Fig. 17.1). Among these, sugar and starch crops are inappropriate for use as energy sources since they are primary food sources, and are unstable from the viewpoints of long-term supply and cost. Cellulosic resources, on the other hand, represent the most abundant global source of biomass, and have been largely unutilised. In one study on fuel ethanol production processes, the efforts were directed toward the use of agricultural waste materials such as bagasse or sugar cane molasses, rice straw, and forestry waste materials such as wood chips from thinning.

## 17.3 Anaerobic digestion

Anaerobic digestion is a series of processes in which micro-organisms break down biodegradable material in the absence of oxygen, used for industrial or domestic purposes to manage waste and/or to release energy. The digestion process begins with bacterial hydrolysis of the input materials in order to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. Acetogenic bacteria then convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. Finally, methanogens convert these products to methane and carbon dioxide (Fig. 17.2).

It is used as part of the process to treat biodegradable waste and sewage sludge. As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere. Anaerobic digesters can also be fed with purpose-grown energy crops such as maize.

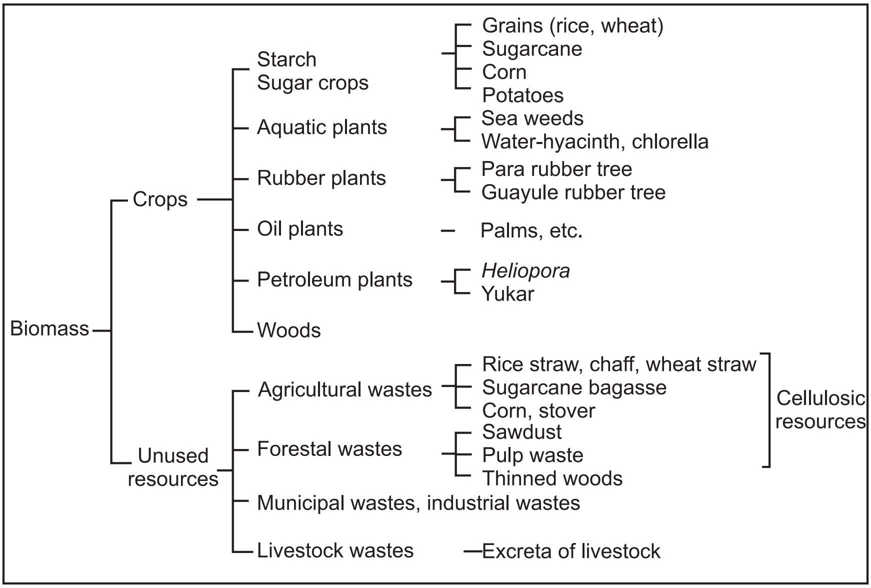



**Figure 17.1** Biomass resources of the world

Anaerobic digestion is widely used as a source of renewable energy. The process produces a biogas, consisting of methane and carbon dioxide. This biogas can be used directly as cooking fuel, in combined heat and power gas engines or upgraded to natural gas quality biomethane. The utilisation of biogas as a fuel helps to replace fossil fuels. The nutrient-rich digestate that is also produced can be used as fertiliser. The technical expertise required to maintain industrial scale anaerobic digesters coupled with high capital costs and low process efficiencies had limited the level of its industrial application as a waste treatment technology. Anaerobic digestion facilities have, however, been recognised by the United Nations Development Program as one of the most useful decentralised sources of energy supply, as they are less capital intensive than large power plants.

## 17.3.1 Applications

Anaerobic digestion is particularly suited to organic material and is commonly used for effluent and sewage treatment. Anaerobic digestion is a simple process that can greatly reduce the amount of organic matter, which might otherwise destined to be dumped at sea, land filled or burnt in an incinerator. Almost any organic material can be processed with anaerobic digestion.

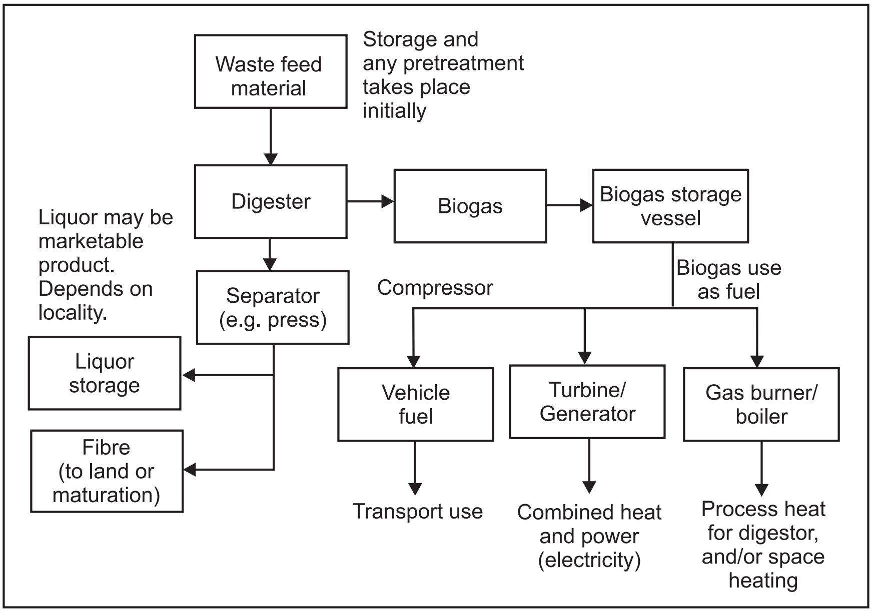



**Figure 17.2** Flow diagram of anaerobic digestion

This includes biodegradable waste materials such as waste paper, grass clippings, leftover food, sewage, and animal waste. The exception to this is woody wastes that are largely unaffected by digestion, as most anaerobes are unable to degrade lignin. The exception being xylophalgeous anaerobes (lignin consumers) or using high temperature pretreatment such as pyrolisis, which breakdown the lignin. Anaerobic digesters can also be fed with specially grown energy crops such as silage for dedicated biogas production. In Germany and continental Europe, these facilities are referred to as biogas plants. A co-digestion or co-fermentation plant is typically an agricultural anaerobic digester that accepts two or more input materials for simultaneous digestion.

Pressure from environmentally related legislation on solid waste disposal methods in developed countries has increased the application of anaerobic digestion as a process for reducing waste volumes and generating useful by-products. Anaerobic digestion may either be used to process the source separated fraction of municipal waste or alternatively combined with mechanical sorting systems, to process residual mixed municipal waste. These facilities are called mechanical biological treatment plants.

Utilising anaerobic digestion technologies can help to reduce the emission of greenhouse gases in a number of key ways:

1. Replacement of fossil fuels
2. Reducing or eliminating the energy footprint of waste treatment plants
3. Reducing methane emission from landfills
4. Displacing industrially produced chemical fertilisers
5. Reducing vehicle movements
6. Reducing electrical grid transportation losses

Methane and power produced in anaerobic digestion facilities can be utilised to replace energy derived from fossil fuels, and hence reduce emissions of greenhouse gases. This is due to the fact that the carbon in biodegradable material is part of a carbon cycle. The carbon released into the atmosphere from the combustion of biogas has been removed by plants in order for them to grow in the recent past. This could have occurred within the last decade, but more typically within the last growing season. If the plants are regrown, taking the carbon out of the atmosphere once more, the system will be carbon neutral. This contrasts to carbon in fossil fuels that has been sequestered in the earth for many millions of years, the combustion of which increases the overall levels of carbon dioxide in the atmosphere.

If the putrescible waste processed in anaerobic digesters were disposed of in a landfill, it would break down naturally and often anaerobically. In this case, the gas will eventually escape into the atmosphere. As methane is about twenty times more potent as a greenhouse gas than carbon dioxide, this has significant negative environmental effects.

Digester liquor can be used as a fertiliser supplying vital nutrients to soils. The solid, fibrous component of the digested material can be used as a soil conditioner to increase the organic content of soils. The liquor can be used instead of chemical fertilisers that require large amounts of energy to produce and transport. The use of manufactured fertilisers is, therefore, more carbon-intensive than the use of anaerobic digester liquor fertiliser. In countries, such as Spain where there are many organically depleted soils, the markets for the digested solids can be equally as important as the biogas.

In countries that collect household waste, the utilisation of local anaerobic digestion facilities can help to reduce the amount of waste that requires transportation to centralised landfill sites or incineration facilities. This reduced burden on transportation reduces carbon emissions from the collection vehicles. If localised anaerobic digestion facilities are embedded within an electrical distribution network, they can help reduce the electrical losses that are associated with transporting electricity over a national grid.

### 17.3.2 Power generation

Biogas from sewage works is sometimes used to run a gas engine to produce electrical power; some or all of which can be used to run the sewage works. Some waste heat from the engine is then used to heat the digester. It turns out that the waste heat is, in general, enough to heat the digester to the required temperatures. The power potential from sewage works is limited—in the UK there are about 80 MW total of such generation, with potential to increase to 150 MW, which is insignificant compared to the average power demand in the UK of about 35,000 MW. The scope for biogas generation from non-sewage waste biological matter—energy crops, food waste, abattoir waste, etc. is much higher, estimated to be capable of about 3000 MW. Farm biogas plants using animal waste and energy crops are expected to contribute to reducing $CO_2$ emissions and strengthen the grid while providing UK farmers with additional revenues. Some countries offer incentives in the form of, for example, Feed-in Tariffs for feeding electricity onto the power grid in order to subsidise green energy production.

### 17.3.3 Grid injection

Biogas grid-injection is the injection of biogas into the natural gas grid. As an alternative, the electricity and the heat can be used for on-site generation, resulting in a reduction of losses in the transportation of energy. Typical energy losses in natural gas transmission systems range from 1–2 per cent, whereas the current energy losses on a large electrical system range from 5–8 per cent. In October 2010, Didcot Sewage Works became the first in the UK to produce biomethane gas supplied to the national grid, for use in up to 200 homes in Oxfordshire.

### 17.3.4 The process

There are many micro-organisms that are involved in the process of anaerobic digestion including acetic acid-forming bacteria (acetogens) and methane-forming archaea (methanogens). These organisms feed upon the initial feedstock, which undergoes a number of different processes, converting it to intermediate molecules including sugars, hydrogen, and acetic acid, before finally being converted to biogas. Different species of bacteria are able to survive at different temperature ranges. Ones living optimally at temperatures between 35–40°C are called mesophiles or mesophilic bacteria. Some of the bacteria can survive at the hotter and more hostile conditions of 55–60°C; these are called thermophiles or thermophilic bacteria. Methanogens come from the domain of archaea. This family includes species that can grow in the hostile conditions of hydrothermal vents. These species are more resistant to heat and can, therefore, operate at high temperatures, a property that is unique to thermophiles.

As with aerobic systems, the bacteria in anaerobic systems the growing and reproducing micro-organisms within them require a source of elemental oxygen to survive. In an anaerobic system, there is an absence of gaseous oxygen. Gaseous oxygen is prevented from entering the system through physical containment in sealed tanks. Anaerobes access oxygen from sources other than the surrounding air. The oxygen source for these micro-organisms can be the organic material itself or may be supplied by inorganic oxides from within the input material. When the oxygen source in an anaerobic system is derived from the organic material itself, the 'intermediate' end-products are primarily alcohols, aldehydes, and organic acids plus carbon dioxide. In the presence of specialised methanogens, the intermediates are converted to the 'final' end-products of methane, carbon dioxide, and trace levels of hydrogen sulphide. In an anaerobic system the majority of the chemical energy contained within the starting material is released by methanogenic bacteria as methane. Populations of anaerobic micro-organisms typically take a significant period of time to establish themselves to be fully effective. Therefore, it is common practice to introduce anaerobic micro-organisms from materials with existing populations, a process known as 'seeding' the digesters, and typically takes place with the addition of sewage sludge or cattle slurry.

## *Stages*

There are four key biological and chemical stages of anaerobic digestion (Fig. 17.3):

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis

In most cases, biomass is made up of large organic polymers. In order for the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore, hydrolysis of these high-molecular-weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids.

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFAs) with a chain length that is greater than that of acetate must first be catabolised into compounds that can be directly utilised by methanogens.

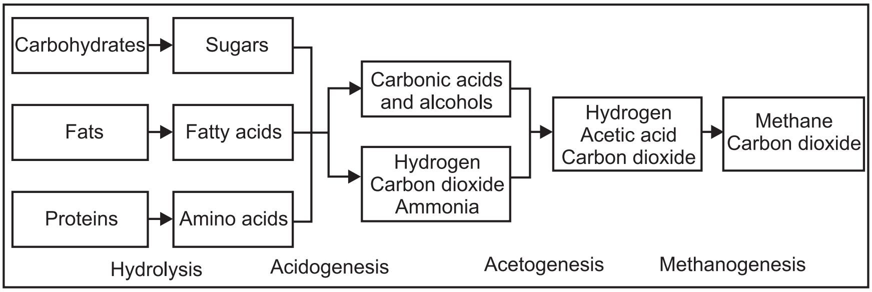



**Figure 17.3** The key process stages of anaerobic digestion

The biological process of acidogenesis is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created along with ammonia, carbon dioxide, and hydrogen sulphide, as well as other by-products. The process of acidogenesis is similar to the way that milk sours.

The third stage of anaerobic digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen. The terminal stage of anaerobic digestion is the biological process of methanogenesis. Here, methanogens utilise the intermediate products of the preceding stages and convert them into methane, carbon dioxide, and water. It is these components that make up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and pH 8. The remaining, non-digestible material that the microbes cannot feed upon, along with any dead bacterial remains, constitutes the digestate. A simplified generic chemical equation for the overall processes outlined above is as follows:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

## 17.3.5 Feedstocks

The most important initial issue when considering the application of anaerobic digestion systems is the feedstock to the process. Digesters typically can accept any biodegradable material; however, if biogas production is the aim, the level of putrescibility is the key factor in its successful application. The more putrescible (digestible) the material the higher the gas yields possible from the system.

Substrate composition is a major factor in determining the methane yield and methane production rates from the digestion of biomass. Techniques to determine the compositional characteristics of the feedstock are available, while parameters such as solids, elemental, and organic analyses are important for digester design and operation.

Anaerobes can break down material with varying degrees of success from readily, in the case of short-chain hydrocarbons such as sugars, to over longer periods of time, in the case of cellulose and hemicellulose. Anaerobic micro-organisms are unable to break down long-chain woody molecules such as lignin. Anaerobic digesters were originally designed for operation using sewage sludge and manures. Sewage and manure are not, however, the material with the most potential for anaerobic digestion, as the biodegradable material has already had much of the energy content taken out by the animal that produced it. Therefore, many digesters operate with co-digestion of two or more types of feedstock. For example, in a farm-based digester that uses dairy manure as the primary feedstock, the gas production may be significantly increased by adding a second feedstock, e.g. grass and corn (typical on-site feedstock) or various organic by-products, such as slaughterhouse waste, fats oils and grease from restaurants, organic household waste, etc. (typical off-site feedstock). Digestors processing dedicated energy crops can achieve high levels of degradation and biogas production. Slurry-only systems are generally cheaper but generate far less energy than those using crops such as maize and grass silage; by using a modest amount of crop material (30 per cent), an AD plant can increase energy output tenfold for only three times the capital cost, relative to a slurry-only system.

A second consideration related to the feedstock is moisture content. Dryer, stackable substrates, such as food- and yard-waste, are suitable for digestion in tunnel-like chambers. Tunnel-style systems typically have near-zero waste-water discharge as well, so this style of system has advantages where the discharge of digester liquids is a liability. The wetter the material the more suitable it will be to handling with standard pumps instead of energy intensive concrete pumps and physical means of movement. Also the wetter the material the more volume and area it takes up relative to the levels of gas that are produced. The moisture content of the target feedstock will also affect what type of system is applied to its treatment. In order to use a high-solids anaerobic digester for dilute feedstocks, bulking agents such as compost should be applied to increase the solid content of the input material. Another key consideration is the carbon:nitrogen ratio of the input material. This ratio is the balance of food a microbe requires in order to grow. The optimal C:N ratio for the ‘food’ a microbe is 20–30:1. Excess N can lead to ammonia inhibition of digestion.

The level of contamination of the feedstock material is a key consideration. If the feedstock to the digesters has significant levels of physical contaminants such as plastic, glass, or metals, then preprocessing will be required in order for the material to be used. If it is not removed then the digesters can be blocked and will not function efficiently. It is with this understanding that mechanical biological treatment plants are designed. The higher the level of pretreatment a feedstock requires the more processing machinery will be required, and, hence, the project will have higher capital costs.

After sorting or screening to remove any physical contaminants, such as metals, and plastics from the feedstock, the material is often shredded, minced, and mechanically or hydraulically pulped to increase the surface area available to microbes in the digesters and, hence, increase the speed of digestion. The maceration of solids can be achieved by using a chopper pump to transfer the feedstock material into the airtight digester, where anaerobic treatment takes place.

### 17.3.6 Configuration

Anaerobic digesters can be designed and engineered to operate using a number of different process configurations:

1. Batch or continuous
2. Temperature: Mesophilic or thermophilic
3. Solids content: High solids or low solids
4. Complexity: Single stage or multistage

#### *Batch or continuous*

A batch system is the simplest form of digestion. Biomass is added to the reactor at the start of the process in a batch and is sealed for the duration of the process. Batch reactors suffer from odour issues that can be a severe problem when they are emptied. In a typical scenario, biogas production will be formed with a normal distribution pattern over time. Operator can use this fact to determine when they believe the process of digestion of the organic matter has completed. As the batch digestion is simple and requires less equipment and lower levels of design work, it is typically a cheaper form of digestion.

In continuous digestion processes, organic matter is constantly added (continuous complete mixed) or added in stages to the reactor (continuous plug flow; first in—first out). Here, the end-products are constantly or periodically removed, resulting in constant production of biogas. A single or multiple digesters in sequence may be used. Examples of this form of anaerobic digestion include continuous stirred-tank reactors (CSTRs), upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB) and internal circulation reactors (IC).

## *Temperature*

There are two conventional operational temperature levels for anaerobic digesters, which are determined by the species of methanogens in the digesters:

1. Mesophilic, which takes place optimally around 30–38°C or at ambient temperatures between 20°C and 45°C where mesophiles are the primary micro-organism present.
2. Thermophilic, which takes place optimally around 49°–57°C at elevated temperatures up to 70°C where thermophiles are the primary micro-organisms present.

A limit case has been reached in Bolivia, with anaerobic digestion in temperature working conditions less than 10°C. The anaerobic process is very slow, taking more than three times the normal mesophilic time process. In experimental work at University of Alaska Fairbanks, a 1000 litre digester using psychrophiles harvested from ‘mud from a frozen lake in Alaska’ has produced 200–300 litres of methane per day, about 20–30 per cent of the output from digesters in warmer climates.

There are a greater number of species of mesophiles than thermophiles. These bacteria are also more tolerant to changes in environmental conditions than thermophiles. Mesophilic systems are, therefore, considered to be more stable than thermophilic digestion systems.

As mentioned above, thermophilic digestion systems are considered to be less stable, the energy input is higher, and more energy is removed from the organic matter. However, the increased temperatures facilitate faster reaction rates and, hence, faster gas yields. Operation at higher temperatures facilitates greater sterilisation of the end-digestate. Certain processes shred the waste finely and use a short high-temperature and -pressure pretreatment (pasteurisation/hygienisation) stage that significantly enhances the gas output of the following standard mesophilic stage. The hygienisation process is also applied in order to reduce the pathogenic micro-organisms in the feedstock. Hygienisation/pasteurisation may be achieved by using a Landia BioChop hygienisation unit or similar method of combined heat treatment and solids maceration. A drawback of operating at thermophilic temperatures is that more heat energy input is required to achieve the correct operational temperatures. This increase in energy may not be outweighed by the increase in the outputs of biogas from the systems. Therefore, it is important to consider an energy balance for these systems.

## Solids

In a typical scenario, there are three different operational parameters associated with the solids content of the feedstock to the digesters:

1. High-solids (dry—stackable substrate)
2. High-solids (wet—pumpable substrate)
3. Low-solids (wet—pumpable substrate)

High-solids (dry) digesters are designed to process materials with a high-solids content between ~25–40 per cent. Unlike wet digesters that process pumpable slurries, high-solids (dry—stackable substrate) digesters are designed to process solid substrates without the addition of water. There are three primary styles of dry digesters: continuous vertical plug flow and batch tunnel horizontal digesters. Continuous vertical plug flow is upright, cylindrical tanks where feedstock is continuously fed to the top of the digester and flows downward by gravity during digestion. In batch tunnel digesters, the feedstock is deposited in tunnel-like chambers with a gastight door.

Neither approach has mixing inside the digester. The amount of pretreatment such as contaminant removal depends both upon the nature of the waste streams being processed and the desired quality of the digestate. Grinding for size reduction is beneficial in continuous vertical systems as it accelerates digestion, while batch systems avoid grinding and instead require structure (e.g. yard waste) to reduce compaction of the stacked pile.

Continuous vertical dry digesters have a smaller footprint due to the shorter effective retention time and vertical design. Wet digesters can be designed to operate in either a high-solids content, with a total suspended solids (TSS) concentration greater than ~20 per cent or a low-solids concentration less than ~15 per cent.

High-solids (wet) digesters process a thick slurry that requires more energy input to move and process the feedstock. The thickness of the material may also lead to associated problems with abrasion. High-solids digesters will typically have a lower land requirement due to the lower volumes associated with the moisture. High-solids digesters require correction of conventional performance calculations (e.g. gas production, retention time, kinetics, etc.) originally based on very dilute sewage digestion concepts, since larger fractions of the feedstock mass are potentially convertible to biogas.

Low-solids (wet) digesters can transport material through the system using standard pumps that require significantly lower energy input. Low-solids digesters require a larger amount of land than high-solids due to the increase volumes associated with the increased liquid-to-feedstock ratio of the digesters. There are benefits associated with operation in a liquid environment, as it enables more thorough circulation of materials and contact between the bacteria and their food. This enables the bacteria to more readily access the substances they are feeding off and increases the speed of gas yields.

### *Number of stages*

Digestion systems can be configured with different levels of complexity:

1. One-stage or single-stage
2. Two-stage or multistage

A single-stage digestion system is one in which all of the biological reactions occur within a single sealed reactor or holding tank. Utilising a single-stage reduces construction costs, however facilitates less control of the reactions occurring within the system. Acidogenic bacteria, through the production of acids, reduce the pH of the tank. Methanogenic bacteria, as outlined earlier, operate in a strictly defined pH range. Therefore, the biological reactions of the different species in a single-stage reactor can be in direct competition with each other. Another one-stage reaction system is an anaerobic lagoon. These lagoons are pond-like earthen basins used for the treatment and long-term storage of manures. Here the anaerobic reactions are contained within the natural anaerobic sludge contained in the pool.

In a two-stage or multistage digestion system, different digestion vessels are optimised to bring maximum control over the bacterial communities living within the digesters. Acidogenic bacteria produce organic acids and more quickly grow and reproduce than methanogenic bacteria. Methanogenic bacteria require stable pH and temperature in order to optimise their performance.

Under typical circumstances, hydrolysis, acetogenesis, and acidogenesis occur within the first reaction vessel. The organic material is then heated to the required operational temperature (either mesophilic or thermophilic) prior to being pumped into a methanogenic reactor. The initial hydrolysis or acidogenesis tanks prior to the methanogenic reactor can provide a buffer to the rate at which feedstock is added. Some European countries require a degree of elevated heat treatment in order to kill harmful bacteria in the input waste.

In this instance, there may be a pasteurisation or sterilisation stage prior to digestion or between the two digestion tanks. It should be noted that it is not possible to completely isolate the different reaction phases, and often there is some biogas that is produced in the hydrolysis or acidogenesis tanks.

### *Residence*

The residence time in a digester varies with the amount and type of feed material, the configuration of the digestion system, and whether it be one-stage or two-stage.

In the case of single-stage thermophilic digestion, residence times may be in the region of 14 days, which, compared to mesophilic digestion, is relatively fast. The plug-flow nature of some of these systems will mean that the full degradation of the material may not have been realised in this time-scale. In this event, digestate exiting the system will be darker in colour and will typically have more odour.

In two-stage mesophilic digestion, residence time may vary between 15 and 40 days.

In the case of mesophilic UASB digestion, hydraulic residence times can be (1 hour to 1 day) and solid retention times can be up to 90 days. In this manner, the UASB system is able to separate solid an hydraulic retention times with the utilisation of a sludge blanket. Continuous digesters have mechanical or hydraulic devices, depending on the level of solids in the material, to mix the contents enabling the bacteria and the food to be in contact. They also allow excess material to be continuously extracted to maintain a reasonably constant volume within the digestion tanks.

## 17.3.7 Products

There are three principal products of anaerobic digestion: biogas, digestate, and water.

### *Biogas*

Biogas is the ultimate waste product of the bacteria feeding off the input biodegradable feedstock (the methanogenesis stage of anaerobic digestion is performed by archaea—a micro-organism on a distinctly different branch of the phylogenetic tree of life to bacteria), and is mostly methane and carbon dioxide, with a small amount hydrogen and trace hydrogen sulphide. (As-produced, biogas also contains water vapour, with the fractional water vapour volume a function of biogas temperature). Most of the biogas is produced during the middle of the digestion, after the bacterial population has grown, and tapers off as the putrescible material is exhausted. The gas is normally stored on top of the digester in an inflatable gas bubble or extracted and stored next to the facility in a gas holder (Table 17.1).

The methane in biogas can be burned to produce both heat and electricity, usually with a reciprocating engine or microturbine often in a cogeneration arrangement where the electricity and waste heat generated are used to warm the digesters or to heat buildings. Excess electricity can be sold to suppliers or put into the local grid. Electricity produced by anaerobic digesters is considered to be renewable energy and may attract subsidies. Biogas does not contribute to increasing atmospheric carbon dioxide concentrations because the gas is not released directly into the atmosphere and the carbon dioxide comes from an organic source with a short carbon cycle.

**Table 17.1** Typical composition of biogas.

| Matter | % |
|---|---|
| Methane, $CH_4$ | 50–75 |
| Carbon dioxide, $CO_2$ | 25–50 |
| Nitrogen, $N_2$ | 0–10 |
| Hydrogen, $H_2$ | 0–1 |
| Hydrogen sulphide, $H_2S$ | 0–3 |
| Oxygen, $O_2$ | 0–2 |

Biogas may require treatment or 'scrubbing' to refine it for use as a fuel. Hydrogen sulphide is a toxic product formed from sulphates in the feedstock and is released as a trace component of the biogas. National environmental enforcement agencies such as the US Environmental Protection Agency? or the English and Welsh Environment Agency put strict limits on the levels of gases containing hydrogen sulphide, and, if the levels of hydrogen sulphide in the gas are high, gas scrubbing and cleaning equipment (such as amine gas treating) will be needed to process the biogas to within regionally accepted levels. An alternative method to this is by the addition of ferrous chloride $FeCl_2$ to the digestion tanks in order to inhibit hydrogen sulphide production.

Volatile siloxanes can also contaminate the biogas; such compounds are frequently found in household waste and waste-water. In digestion facilities accepting these materials as a component of the feedstock, low-molecular-weight siloxanes volatilise into biogas. When this gas is combusted in a gas engine, turbine or boiler, siloxanes are converted into silicon dioxide ($SiO_2$), which deposits internally in the machine, increasing wear and tear. Practical and cost-effective technologies to remove siloxanes and other biogas contaminants are available at the present time. In certain applications, in situ treatment can be used to increase the methane purity by reducing the off-gas carbon dioxide content, purging the majority of it in a secondary reactor.

In countries such as Switzerland, Germany, and Sweden, the methane in the biogas may be concentrated in order for it to be used as a vehicle transportation fuel or input directly into the gas mains. In countries where the driver for the utilisation of anaerobic digestion are renewable electricity subsidies, this route of treatment is less likely, as energy is required in this processing stage and reduces the overall levels available to sell.

## *Digestate*

Digestate is the solid remnants of the original input material to the digesters that the microbes cannot use. It also consists of the mineralised remains of the dead bacteria from within the digesters. Digestate can come in three forms: fibrous, liquor or a sludge-based combination of the two fractions. In two-stage systems, the different forms of digestate come from different digestion tanks. In single-stage digestion systems, the two fractions will be combined and, if desired, separated by further processing.

The second by-product (acidogenic digestate) is a stable organic material consisting largely of lignin and cellulose, but also of a variety of mineral components in a matrix of dead bacterial cells; some plastic may be present. The material resembles domestic compost and can be used as compost or to make low-grade building products such as fibreboard. The solid digestate can also be utilised as feedstock for ethanol production.

The third by-product is a liquid (methanogenic digestate) that is rich in nutrients and can be used as a fertiliser dependent on the quality of the material being digested. Levels of potentially toxic elements (PTEs) should be chemically assessed. This will be dependent upon the quality of the original feedstock. In the case of most clean and source-separated biodegradable waste streams, the levels of PTEs will be low. In the case of wastes originating from industry, the levels of PTEs may be higher and will need to be taken into consideration when determining a suitable end use for the material.

Digestate typically contains elements such as lignin that cannot be broken down by the anaerobic micro-organisms. Also the digestate may contain ammonia that is phytotoxic and will hamper the growth of plants if it is used as a soil-improving material. For these two reasons, a maturation or composting stage may be employed after digestion. Lignin and other materials are available for degradation by aerobic micro-organisms such as fungi, helping reduce the overall volume of the material for transport. During this maturation, the ammonia will be broken down into nitrates, improving the fertility of the material and making it more suitable as a soil improver. Large composting stages are typically used by dry anaerobic digestion technologies.

### *Waste-water*

The final output from anaerobic digestion systems is water. This water originates both from the moisture content of the original waste that was treated but also includes water produced during the microbial reactions in the digestion systems. This water may be released from the dewatering of the digestate or may be implicitly separate from the digestate.

The waste-water exiting the anaerobic digestion facility will typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). These are measures of the reactivity of the effluent and show an ability to pollute. Some of this material is termed ‘hard COD’, meaning that it cannot be accessed by the anaerobic bacteria for conversion into biogas. If this effluent were put directly into watercourses, it would negatively affect them by causing eutrophication. As such, further treatment of the waste-water is often required. This treatment will typically be an oxidation stage wherein air is passed through the water in a sequencing batch reactors or reverse osmosis unit.

## 17.4 Aerobic digestion

Aerobic digestion is a bacterial process occurring in the presence of oxygen. Under aerobic conditions, bacteria rapidly consume organic matter and convert it into carbon dioxide. Once there is a lack of organic matter, bacteria die and are used as food by other bacteria. This stage of the process is known as endogenous respiration. Solids reduction occurs in this phase. Because the aerobic digestion occurs much faster than anaerobic digestion, the capital costs of aerobic digestion are lower. However, the operating costs are characteristically much greater for aerobic digestion because of energy costs for aeration needed to add oxygen to the process.

### 17.4.1 Comparison of anaerobic and aerobic digestion

In both aerobic and anaerobic systems the growing and reproducing microorganisms within them require a source of elemental oxygen to survive (Table 17.2).

**Table 17.2** Anaerobic and aerobic system comparison.

| Anaerobic digestion | Composting |
|---|---|
| Digestate | Compost |
| Carbon dioxide | Carbon dioxide |
| Methane | Heat |
| Hydrogen sulphide (trace levels) | |

In an anaerobic system there is an absence of gaseous oxygen. In an anaerobic digester, gaseous oxygen is prevented from entering the system through physical containment in sealed tanks. Anaerobes access oxygen from sources other than the surrounding air. The oxygen source for these micro-organisms can be the organic material itself or alternatively may be supplied by inorganic oxides from within the input material. When the oxygen source in an anaerobic system is derived from the organic material itself, then the 'intermediate' end products are primarily alcohols, aldehydes, and organic acids plus carbon dioxide. In the presence of specialised methanogens, the intermediates are converted to the 'final' end products of methane, carbon dioxide with trace levels of hydrogen sulphide. In an anaerobic system the majority of the chemical energy contained within the starting material is released by methanogenic bacteria as methane.

In an aerobic system, such as composting, the micro-organisms access free, gaseous oxygen directly from the surrounding atmosphere. The end products of an aerobic process are primarily carbon dioxide and water which are the stable, oxidised forms of carbon and hydrogen. If the biodegradable starting material contains nitrogen, phosphorus and sulphur, then the end products may also include their oxidised forms—nitrate, phosphate and sulphate. In an aerobic system the majority of the energy in the starting material is released as heat by their oxidisation into carbon dioxide and water.

Composting systems typically include organisms such as fungi that are able to break down lignin and celluloses to a greater extent than anaerobic bacteria. It is due to this fact it is possible, following anaerobic digestion, to compost the anaerobic digestate allowing further volume reduction and stabilisation. When considering an overall system energy and carbon balance anaerobic digestion performs better the main alternative, composting.

## 17.5 Components of a biogas system

Biogas technology is a manure management tool that promotes the recovery and use of biogas as energy by adapting manure management practices to collect biogas. The biogas can be used as a fuel source to generate electricity for on-farm use or for sale to the electrical grid or for heating or cooling needs. The biologically stabilised by-products of anaerobic digestion can be used in a number of ways, depending on local needs and resources. Successful by-product applications include use as a crop fertiliser, bedding, and as aquaculture supplements.

A typical biogas system consists of the following components:

1. Manure collection
2. Anaerobic digester

3. Effluent storage
4. Gas handling
5. Gas use

Each of these components is discussed briefly.

### 17.5.1 Manure collection

Livestock facilities use manure management systems to collect and store manure because of sanitary, environmental, and farm operational considerations. Manure is collected and stored as either liquids, slurries, semisolids or solids.

1. *Raw manure:* Manure is excreted with a solids content of 8 to 25 per cent, depending upon animal type. It can be diluted by various process waters or thickened by air drying or by adding bedding materials.
2. *Liquid manure:* Manure handled as a liquid has been diluted to a solids content of less than 5 per cent. This manure is typically 'flushed' from where it is excreted, using fresh or recycled water. The manure and flush water can be pumped to treatment and storage tanks, ponds, lagoons, or other suitable structures before land application. Liquid manure systems may be adapted for biogas production and energy recovery in 'warm' climates. In colder climates, biogas recovery can be used, but is usually limited to gas flaring for odour control.
3. *Slurry manure:* Manure handled as a slurry has been diluted to a solids content of about 5 to 10 per cent. Slurry manure is usually collected by a mechanical 'scraper' system. This manure can be pumped, and is often treated or stored in tanks, ponds, or lagoons prior to land application. Some amount of water is generally mixed with the manure to create a slurry. For example, spilled drinking water mixes with pig manure to create a slurry. Manure managed in this manner may be used for biogas recovery and energy production, depending on climate and dilution factors.
4. *Semisolid manure:* Manure handled as a semisolid has a solids content of 10 to 20 per cent. This manure is typically scraped. Water is not added to the manure, and the manure is typically stored until it is spread on local fields. Fresh scraped manure (less than one week old) can be used for biogas and energy production in all climates, because it can be heated to promote bacterial growth.
5. *Solid manure:* Manure with a solids content of greater than 20 per cent is handled as a solid by a scoop loader. Aged solid manure or manure that is left 'unmanaged' (i.e. is left in the pasture where it is deposited by the animals) or allowed to dry is not suitable for biogas recovery.

## 17.5.2 Digester types

The digester is the component of the manure management system that optimises naturally occurring anaerobic bacteria to decompose and treat the manure while producing biogas. Digesters are covered with an air-tight impermeable cover to trap the biogas for on-farm energy use. The choice of which digester to use is driven by the existing (or planned) manure handling system at the facility. The digester must be designed to operate as part of the facility's operations. One of three basic options will generally be suitable for most conditions. The main characteristics of these digester technologies are:

1. *Covered lagoon digester:* Covered lagoons are used to treat and produce biogas from liquid manure with less than 3 per cent solids. Generally, large lagoon volumes are required, preferably with depths greater than 12 feet. The typical volume of the required lagoon can be roughly estimated by multiplying the daily manure flush volume by 40 to 60 days. Covered lagoons for energy recovery are compatible with flush manure systems in warm climates. Covered lagoons may be used in cold climates for seasonal biogas recovery and odour control (gas flaring). There are two types of covers, bank-to-bank and modular. A bank-to-bank cover is used in moderate to heavy rainfall regions. A modular cover is used for arid regions. Typically, multiple modules cover the lagoon surface and can be fabricated from various materials.
2. *Complete mix digester:* Complete mix digesters are engineered tanks, above or below ground, that treat slurry manure with a solids concentration in the range of 3 to 10 per cent. These structures require less land than lagoons and are heated. Complete mix digesters are compatible with combinations of scraped and flushed manure.
3. *Plug flow digester:* Plug flow digesters are engineered, heated, rectangular tanks that treat scraped dairy manure with a range of 11 to 13 per cent total solids. Swine manure cannot be treated with a plug flow digester due to its lack of fibre.
4. *Fixed film digester:* Fixed-film digesters consist of a tank filled with plastic media. The media supports a thin layer of anaerobic bacteria called biofilm (hence the term 'fixed-film'). As the waste manure passes through the media, biogas is produced. Like covered lagoon digesters fixed-film digesters are best suited for dilute waste streams typically associated with flush manure handling or pit recharge manure collection. Fixed-film digesters can be used for both dairy and swine wastes. However, separation of dairy manure is required to remove slowly degradable solids.

### 17.5.3 Effluent storage

The products of the anaerobic digestion of manure in digesters are biogas and effluent. The effluent is a stabilised organic solution that has value as a fertiliser and other potential uses. Waste storage facilities are required to store treated effluent because the nutrients in the effluent cannot be applied to land and crops year round.

The size of the storage facility and storage period must be adequate to meet farm requirements during the non-growing season. Facilities with longer storage periods allow flexibility in managing the waste to accommodate weather changes, equipment availability and breakdown, and overall operation management.

### 17.5.4 Gas handling

A gas handling system removes biogas from the digester and transports it to the end-use, such as an engine or flange. Gas handling includes: piping; gas pump or blower; gas meter; pressure regulator; and condensate drain(s).

Biogas produced in the digester is trapped under an airtight cover placed over the digester. The biogas is removed by pulling a slight vacuum on the collection pipe (e.g. by connecting a gas pump/blower to the end of the pipe), which draws the collected gas from under the cover. A gas meter is used to monitor the gas flow rate. Sometimes a gas scrubber is needed to clean or 'scrub' the biogas of corrosive compounds contained in the biogas (e.g. hydrogen sulphide). Warm biogas cools as it travels through the piping and water vapour in the gas condenses. A condensate drain(s) removes the condensate produced.

### 17.5.5 Gas use

Recovered biogas can be utilised in a variety of ways. The recovered gas is 60–80 per cent methane, with a heating value of approximately 600–800 Btu/ft3. Gas of this quality can be used to generate electricity; it may be used as fuel for a boiler, space heater, or refrigeration equipment; or it may be directly combusted as a cooking and lighting fuel.

Electricity can be generated for on-farm use or for sale to the local electric power grid. The most common technology for generating electricity is an internal combustion engine with a generator. The predicted gas flow rate and the operating plan are used to size the electricity generation equipment.

Engine-generator sets are available in many sizes. Some brands have a long history of reliable operation when fuelled by biogas. Electricity generated in this manner can replace energy purchased from the local utility or can be sold directly to the local electricity supply system. In addition, waste heat from these engines can provide heating or hot water for farm use.

Biogas can also be used directly on-site as a fuel for facility operations. Equipment that normally uses propane or natural gas can be modified to use biogas. Such equipment includes boilers, heaters, and chillers.

1. *Boilers and space heaters:* Boilers and space heaters fired with biogas produce heat for use in the facility operations. Although this may not be the most efficient use of the gas, in some situations it may be a farm's best option.
2. *Chilling/Refrigeration:* Dairy farms use considerable amounts of energy for refrigeration. Approximately 15 to 30 per cent of a dairy's electricity load is used to cool milk. Gas-fired chillers are commercially available and can be used for this purpose. For some dairies, this may be the most cost effective option for biogas utilisation.

Other energy use options may exist. For example, a nearby greenhouse could be heated with the biogas, and carbon dioxide from the heater exhaust could be used to enhance plant growth. These options need to be evaluated on a case-by-case basis.

### 17.5.6 Benefits of biogas technology

Most confined livestock operations handle manure as liquids, slurries, semisolids or solids that are stored in lagoons, concrete basins, tanks, and other containment structures. These structures are typically designed to comply with local and state environmental regulations and are a necessary cost of production.

Biogas technology can be a cost-effective, environment and neighbourhood friendly addition to existing manure management strategies. Biogas technologies anaerobically digest manure, resulting in biogas and a liquefied, low-odour effluent. By managing the anaerobic digestion of manure, biogas technologies significantly reduce biochemical oxygen demand (BOD), and pathogen levels; remove most noxious odours; and convert most of the organic nitrogen to plant available inorganic nitrogen.

The principal reasons a farmer or producer would consider installing a biogas system are:

1. *On-site farm energy:* By recovering biogas and producing on-farm energy, livestock producers can reduce monthly energy purchases from electric and gas suppliers.
2. Reduced odours. Biogas systems reduce offensive odours from overloaded or improperly managed manure storage facilities. These odours impair air quality and may be a nuisance to nearby communities. Biogas systems reduce these offensive odours because the volatile organic acids, the odour causing compounds, are consumed by biogas producing bacteria.

3. *High quality fertiliser:* In the process of anaerobic digestion, the organic nitrogen in the manure is largely converted to ammonium. Ammonium is the primary constituent of commercial fertiliser, which is readily available and utilised by plants.
4. Reduced surface and groundwater contamination. Digester effluent is a more uniform and predictable product than untreated manure. The higher ammonium content allows better crop utilisation and the physical properties allow easier land application. Properly applied, digester effluent reduces the likelihood of surface or groundwater pollution.
5. *Pathogen reduction:* Heated digesters reduce pathogen populations dramatically in a few days. Lagoon digesters isolate pathogens and allow pathogen kill and die-off prior to entering storage for land application.

Biogas recovery can improve profitability while improving environmental quality. Maximising farm resources in such a manner may prove essential to remain competitive and environmentally sustainable in today's livestock industry. In addition, more widespread use of biogas technology will create jobs related to the design, operation, and manufacture of energy recovery systems and lead to the advancement of agribusiness around the world.

### 17.5.7 Reasons for failure

Biogas recovery projects failed because:

1. Operators did not have the skills or the time required to keep a marginal system operating.
2. Producers selected digester systems that were not compatible with their manure handling methods.
3. Some designer/builders sold 'cookie cutter' designs to farms. For example, of the 30 plug flow digesters built, 19 were built by one designer and 90 per cent failed.
4. The designer/builders installed the wrong type of equipment, such as incorrectly sized engine-generators, gas transmission equipment, and electrical relays.
5. The systems became too expensive to maintain and repair because of poor system design.
6. Farmers did not receive adequate training and technical support for their systems.
7. There were no financial returns of the system or returns diminished over time.
8. Farms went out of business due to non-digester factors.

### 17.5.8 Today's experiences

The development of anaerobic digesters for livestock manure treatment and energy production has accelerated at a very face pace over the past few years. Factors influencing this market demand include: increased technical reliability of anaerobic digesters through the deployment of successful operating systems over the past decade; growing concern of farm owners about environmental quality; an increasing number of states and federal programs designed to cost share in the development of these systems; and the emergence of new state energy policies designed to expand growth in reliable renewable energy and green power markets.

## 17.6 Biogas as transportation fuel

Biogas is used as transportation fuel in a number of countries, but in Europe it has only reached a major breakthrough in Sweden. All of the biogas plants in Sweden that are in the planning or construction phase will be equipped with possibilities to deliver a biogas that is upgraded to natural gas quality, either for direct use as vehicle fuel or for injection into the natural gas grid. The development of biogas as vehicle fuel in Sweden is a result of a combination of a surplus of gas from biogas plants, primarily at the sewage treatment plants, and a low electricity price that forces the biogas into markets other than electricity production. The supply of petroleum fuels will gradually decrease and these will have to be replaced by sustainable fuels. In the short-term this means that biofuels that already are present on the market where suitable vehicle technology is available (biogas, ethanol, biodiesel) must be used and development activities in order to develop long-term alternatives (e.g. hydrogen) must be intensified. Biogas is a biofuel that in Europe in general has mainly been regarded as a fuel suitable for electricity generation in gas engines. Biogas can just be used in vehicle engines as well, and there are more than 4000 vehicles in Sweden running on biogas and natural gas today.

### 17.6.1 Sources of biogas

Biogas comes from four main sources:

1. *Sewage treatment plants:* Many sewage treatment plants produce methane rich gases in the sludge fermentation stage. Utilisation of methane from sewage plants is used on a large scale in many countries. Optimised process conditions can enhance the production and collection of these gases.

2. *Landfills:* All landfills produce methane rich gases. Collection and utilisation of the gases is applied quite widely. Improved collection, processing and utilisation of landfill gases will be an important tool to increase the importance of landfill gas.
3. *Cleaning of organic industrial waste streams:* Anaerobic digestion processes are often successfully applied to clean the waste streams of agricultural processing industry. The methane rich gases are mainly utilised to produce electricity and heat in local co-generation plants.
4. *Mesophilic and thermophilic digestion of organic waste:* Compact installations convert organic waste to methane rich gases at higher temperatures. The main difference between the two methods is the digestion temperature (35°C in the mesophilic process and 55°C in the other mesophilic process).

### 17.6.2 Upgrading of biogas to natural gas quality

Biogas has to be upgraded to natural gas quality in order to be used in normal vehicles designed to use natural gas. The most common technologies are the water scrubber technology and the PSA-technology. Gas upgrading is normally performed in two steps where the main step is the process that removes the $CO_2$ from the gas. Minor contaminants are normally removed before the $CO_2$-removal and the water dew point can be adjusted before or after the upgrading (depending on the process).

#### *Water scrubber technology*

Two types of water absorption processes are commonly used for upgrading of gas from anaerobic digestion, single pass absorption and regenerative absorption. The major difference between the two processes is that the water in the single pass process is used only once. A typical installation is at a sewage water treatment plant. Water can also be recycled and in this case a stripper column has to be integrated in the process (regenerative absorption). The single pass process is described below. Cleaned sewage water has a sufficient quality for use in the absorption column. After the flash tank the water is depressurised by a regulator valve and returned to the sewage water treatment system (Fig. 17.4).

#### *Pressure swing adsorption (PSA) technology*

Pressure swing adsorption or PSA, is a method for the separation of carbon dioxide from methane by adsorption/desorption of carbon dioxide on zeolites or activated carbon at different pressure levels. The adsorption material adsorbs hydrogen sulphide irreversibly and thus is poisoned by hydrogen sulphide. For this reason a hydrogen sulphide removing step is often included in the PSA process.

The upgrading system consists of four adsorber vessels filled with adsorption material. During normal operation each adsorber operates in an alternating cycle of adsorption, regeneration and pressure build-up. During the adsorption phase biogas enters from the bottom into one of the adsorbers. When passing the adsorber vessel, carbon dioxide, oxygen and nitrogen are adsorbed on the adsorbent material surface. The gas leaving the top of the adsorber vessel contains >97 per cent methane.

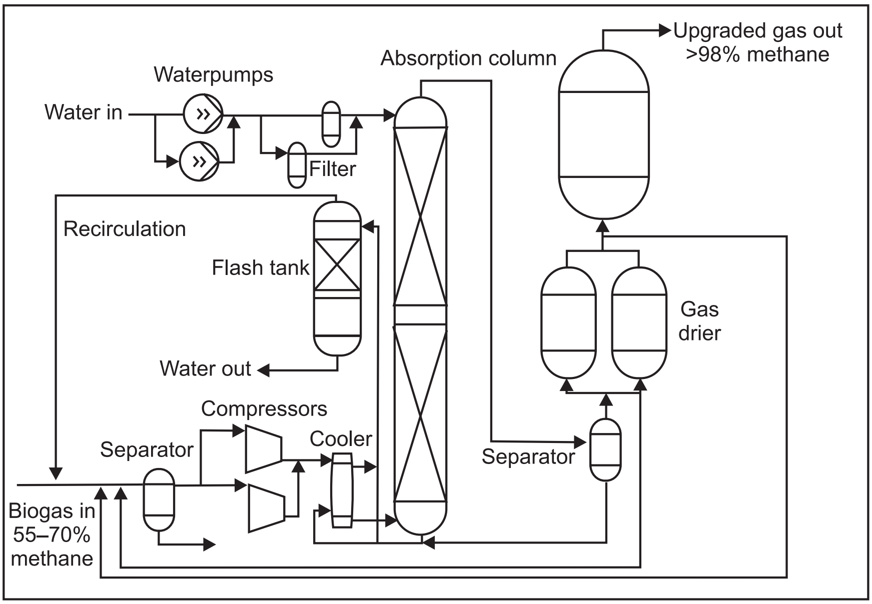



**Figure 17.4** Removal of carbon dioxide using water wash without regeneration

Before the adsorbent material is completely saturated with the adsorbed feed gas components, the adsorption phase is stopped and another adsorber vessel that has been regenerated is switched into adsorption mode to achieve continuous operation.

Regeneration of the saturated adsorbent material is performed by a stepwise depressurisation of the adsorber vessel to atmospheric pressure and finally to near vacuum conditions. Initially the pressure is reduced by a pressure balance with an already regenerated adsorber vessel.

This is followed by a second depressurisation step to almost atmospheric pressure. The gas leaving the vessel during this step contains significant amounts of methane and is recycled to the gas inlet.

Before the adsorption phase starts again, the adsorber vessel is repressurised stepwise to the final adsorption pressure. After a pressure balance with an adsorber that has been in adsorption mode before, the final pressure build-up is achieved with feed gas.

## *Other technologies*

In some cases membrane technologies have been used for gas upgrading. The membrane technology has a potential to be energy efficient but for the moment there is very limited experience in Sweden of this technology. Chemical adsorption technologies seem to be an attractive solution due to low methane losses and high selectivity. The process requires a rather high input of thermal energy for the regeneration of the chemical but can on the other hand be operated at low pressure that reduces the electrical energy demand of the process.

## *Biogas vehicles*

Biogas can be used in both heavy duty and light duty vehicles. Light duty vehicles can normally run both on natural gas and biogas without any modifications, whereas heavy duty vehicles without closed loop control may have to be adjusted, if they run alternately on biogas and natural gas.

Sweden is the only country in the world with a national standard for biogas as vehicle fuel today. This standard essentially states that the methane content must be higher than 95 per cent and also sets limits for dew point, sulphur content and some other minor constituents.

Today there are more than 4000 vehicles in Sweden running on natural gas and biogas and several local fleets (e.g. Linköping, Uppsala, Kristianstad) where the major part of the urban public transports are operated on biogas.

Biogas the pathway to hydrogen

Biogas can be regarded as one possible way to gradually change over to hydrogen as energy carrier. There are many similarities:

1. Hydrogen (if produced from sustainable sources) and biogas are both renewable fuels.
2. Hydrogen and biogas can both be distributed on the natural gas grid.
3. Hydrogen and biogas can be used in natural gas vehicles.
4. The first European tests with hydrogen/natural gas mixtures in buses are now carried out in Malmö, Sweden.

The introduction of biogas as a vehicle fuel in Sweden has been based on a solid co-operation between the natural gas utilities and the biogas producers. This has resulted in an understanding for gas quality aspects and other technical issues that have to be dealt with when introducing both biogas and hydrogen as vehicle fuels. Thus, the natural gas is a fossil fuel that has many advantages (high security of supply, low emissions, established distribution grid, etc.) compared to liquid fuels like diesel and gasoline and has also been pointed out as a major alternative in the changeover to sustainable fuels. Upgraded biogas has the same advantages as natural gas, but additionally is a sustainable fuel that can be manufactured from local waste streams thereby also solving local waste problems.

Production of biogas is a mature technology that is well established in many European countries and the biogas potential is considerable, especially when taking into account the possibilities to use set aside land for production of crops for biogas.

Upgrading of biogas is a relatively new technology but experience from Sweden and other countries shows that it is possible now to upgrade biogas with high reliability and at reasonable costs. The Swedish experience shows that biogas can be an economical sustainable fuel with a potential to drastically reduce emissions in urban transport.

## 17.7 Biogas problems

Biogas is really no more dangerous than other fuels such as wood, gasoline or bottled gas. But just as these fuels have their ways of being dangerous, so does biogas. Face it; anything that can cook meals and fuel an engine can also burn people.

Certain precautions should be observed in the operation of biogas systems. Biogas can be explosive when mixed with air in the proportion of one part biogas to 8–20 parts air in an enclosed space. This situation can occur when a digester is opened for cleaning, when biogas is released to repair a gas storage tank or when there is a gas leak in a poorly ventilated room. In such cases, avoid sparks, smoking, and open flames.

A biogas leak can be smelled if the hydrogen sulphide has not been removed from the biogas. It smells like rotten eggs. No one should go inside large digesters unless they have a companion on the outside who can get them out in case they need help. Although the methane and carbon dioxide of biogas are not poisonous, a person may stop breathing if there is too much biogas and not enough oxygen in the air they are trying to breath. Never allow negative pressure in a biogas system. Negative pressure occurs when the force created by the weight of the gases outside the biogas system is greater than the force inside the system. In normal operations the pressure inside the system should always be greater. How much greater should always be measured on a pressure gauge.

Negative pressure will pull air into the biogas system and the mixture of biogas and air might explode. If that does not happen, the oxygen in the air will kill the biogas bacteria and the gas production rate will drop. The only time the danger of negative pressure usually becomes a real possibility is when a person wants more gas from a digester than it can produce or there is an unnoticed gas leak.

When biogas is used at pressures below one column inch of water as measured on a pressure gauge, it is very likely that the flame will go out. Even though there is not much gas left in the system, biogas will continue to come out. Then the possibility for a spark or flame causing an explosion in the room or negative pressure pulling air into the biogas system causing an explosion in the system, becomes real. When opening a biogas digester for cleaning or repairing, do not use candles or smoke cigarettes. For light inside the digester, use a flashlight or have a person standing outside reflect sunlight off a mirror. Make frequent smell checks for gas leaks in plastic pipes, joints, clamps, and gate valves. Rats have been known to bite holes in plastic pipes. Stoves and gas mantle lamps should be placed with fire safety in mind. Special care must be taken in buildings with grass roofs to make sure that gas lamps are a good distance from the roof.

If the rotten egg smell of biogas is noticed in a room, immediately open doors and windows in order to get rid of the trapped gas before looking for the leak. On no account should anyone smoke cigarettes in the room. In case of fire in a house or engine room, shut the gas off at the gate valve just after the gas storage tank to keep biogas from feeding the fire.

When using any kind of gas, light the match first, then open the gas valve. If the valve is opened first and gas is allowed to flow without being lit for any length of time, large amounts of gas can escape and any flame might ignite a fireball. Children must be taught not to play with fire close to biogas systems, in case there are any gas leaks which could cause a fire or explosion. Brass gate valves and pipes used in biogas systems must be of a lead-free type. The hydrogen sulphide in biogas will destroy lead, which will cause gas leaks.

The following flame arrester suggestion is adapted from the Guidebook on Biogas Development. A flame arrester is a safety device that should be added to every gas line. It is usually placed either just after the gate valve at the digester and just before the gas stove or stationary engine. Its purpose is, in case of fire, to prevent the flame from travelling down the gas pipe into the gas storage tank or digester and causing an explosion. The arrester can be a ball or roll of fine mesh copper wire (iron and steel would rust) inserted into the gas pipe. It is sometimes not realised that this forms a barrier to the free and full flow of gas. It is recommended that the flame arrester be placed in a length of pipe of slightly larger diameter than the gas pipe. For a 0.5 inch pipe use a 0.75 inch arrester pipe; for a 1.0 inch pipe use a 1.25 inch arrester pipe. It is very important that if a digester is built underground, that it is built in a place that never floods. If an above ground digester is built in an area that sometimes floods, make sure that the openings into the digester are above the high water mark. If a digester is built in an area that does have floods, safety measures should be taken in advance so that the gas can escape in case the digester and/or the gas storage tank are flooded. Failure to do so could result in dangerous, uncontrolled release of biogas and if the digester is a plastic bag, it could float up and away. An upside-down 'T' pipe should be placed at the highest vertical point in the gas pipeline above the gas outlet from the digester. A vertical pipe and a gate valve should be joined to the stem of the upside-down 'T' pipe. The gate valve can then be opened to release the biogas if a flood threatens to cover either the digester or the gas storage tank.

### 17.7.1 Safety measures

The following is a list of safety measures that should be read with great care before a biogas system is built.

1. Regularly check the whole system for leaks.
2. Provide ventilation around all gas lines.
3. Always maintain a positive pressure in the system.
4. The engine room floor must be at or above ground level to avoid the build-up of heavier-than- air gases.
5. The engine room roof must be vented at its highest point to allow lighter-than-air gases to escape. This is also true for greenhouses that have biogas digesters, engines or burners in them.
6. The engine exhaust pipe must be extended so that the dangerous and deadly exhaust gases are released outside the building.
7. Metal digesters and gas storage tanks must have wires to lead lightning to the ground.
8. Gas lines must drain water into condensation traps.
9. No smoking or open flames should be allowed near biogas digesters and gas storage tanks, especially when checking for gas leaks.

Methane, the flammable part of biogas, is a lesser danger to life than many other fuels. However, in the making and using of an invisible fuel, dangerous situations can arise unexpectedly and swiftly—such as when a gas pipe is accidently cut. On the other hand, precaution can be exaggerated. When cars first appeared on the roads, a man waving a red flag came first.

### *Health hazards*

Health hazards are associated with the handling of night soil and with the use of sludge from untreated human excrete as fertiliser. In general, published data indicate that a digestion time of 14 days at 35°C is effective in killing (99.9 per cent die-off rate) the enteric bacterial pathogens and the enteric group of viruses. However, the die-off rate for roundworm (Ascaris lumbricoides) and hookworm (Ancylostoma) is only 90 per cent, which is still high. In this context, biogas production would provide a public health benefit beyond that of any other treatment in managing the rural health environment of developing countries.

## 17.7.2 Bottlenecks, considerations and research and development

Bioconversion of organic domestic and farm residues has become attractive as its technology has been successfully tested through experience on both small- and large-scale projects. Feeding upon renewable resources and non-polluting in process technology, biogas generation serves a triple function: waste removal, management of the environment, and energy production. Nevertheless, there are still several problems that impede the efficient working of biogas generating systems (Table 17.3).

**Table 17.3** Considerations relating to bottlenecks in biogas generation.

| Aspect | Bottlenecks | Remarks |
|---|---|---|
| Planning | Availability and ease of transportation of raw materials and processed residual products | Use of algae and hydroponic plants offsets high transportation costs of materials not readily at hand. Easily dried residual products facilitate transportation. |
| | Site selection | Nature of subsoil, water table, and availability of solar radiation, prevailing climatic conditions, and strength of village population need to be considered. |
| | Financial constraints: Digester design; high transportation costs of digester materials; installation and maintenance costs; increasing labour costs in distribution of biogas products for domestic purposes | Use of cheap construction materials, emphasising low capital and maintenance costs and simplicity of operation; provision of subsidies and loans that are not burdensome. |

*cont...*

*cont...*

| Aspect | Bottlenecks | Remarks |
|---|---|---|
| | Necessity to own or have access to relatively large number of cattle | Well-planned rural community development, ownership and biogas distribution schemes necessary. |
| | Social constraints and psychological prejudice against the use of raw materials | Development of publicity programs to counteract constraints compounded by illiteracy; provision of incentives for development of small-scale integrated biogas systems. |
| Technical | Improper preparation of influent solids leading to blockage and scum formation | Proper milling and other treatment measures (pre-soaking, adjustment of C/N ratio); removal of inert particles: sand and rocks. |
| | Temperature fluctuations | Careful regulation of temperature through use of low-cost insulating materials (sawdust, bagasse, grass, cotton waste, wheat straw); incorporation of auxiliary solar heating system. |
| | Maintenance of pH for optimal growth of methanogenic bacteria C/N ratio | Appropriate choice of raw material, regulation of C/N ratio and dilution rate. Appropriate mixing of N-rich and N-poor substrates with cellulosic substrates. |
| | Dilution ratio of influent solids content | Appropriate treatment of raw materials to avoid stratification and scum formation. |
| | Retention time of slurry | Dependent upon dilution ratio, loading rate, digestion temperature. |
| | Loading rate | Dependent upon digester size, dilution ratio, digestion temperature. |
| | Seeding of an appropriate bacterial population for biogas generation | Development of specific and potent cultures. |
| | Corrosion of gas holder | Construction from cheap materials (glass fibre, clay, jute-fibre reinforced plastic) and/or regular cleaning and layering with protective materials (e.g. lubricating oil). |

*cont...*

cont...

| Aspect | Bottlenecks | Remarks |
|---|---|---|
| | Pin-hole leakages (digester tank, holder, inlet, outlet) | Establishment of 'no leak' conditions, use of external protective coating materials |
| | Occurrence of $CO_2$ reducing calorific value of biogas | Reduction in $CO_2$ content through passage in lime-water |
| | Occurrence of water condensate in gas supply system (blockage, rusting) | Appropriate drainage system using condensate traps |
| | Occurrence of $H_2S$ leading to corrosion | On a village scale, $H_2S$ removed by passing over ferric oxide or iron filings |
| | Improper combustion | Designing of air-gas mixing appliances necessary |
| | Maintenance of gas supply at constant pressure | Regulation of uniform distribution and use of gas; removal of water condensate from piping systems; appropriate choice of gas holder in terms of weight and capacity |
| Residue utilisation | Risks to health and plant crops resulting from residual accumulation of toxic materials and encysted pathogens | Avoid use of chemical industry effluents; more research on type, nature, and die-off rates of persisting organisms; minimise long transportation period of un-dried effluent |
| Health | Hazards to human health in transporting night soil and other wastes (gray-water) | Linkage of latrine run-offs into biogas reactors promotes non-manual operations and general aesthetics |
| Safety | Improper handling and storage of methane | Appropriate measures necessary for plant operation, handling, and storage of biogas through provision of extension and servicing facilities. |

Rural communities using the integrated system are appropriate examples of recycled societies that benefit from low-capital investments on a decentralised basis and such communities are attuned to the environment. The technology thus seeded and spawned is, in essence, a populist technology based on 'nature's income and not on nature's capital'.

Biogas generated from locally available waste material seems to be one of the answers to the energy problem in most rural areas of developing countries. Gas generation consumes about one-fourth of the dung, but the available heat of the gas is about 20 per cent more than that obtained by burning the entire amount of dung directly. This is mainly due to the very high efficiency (60 per cent) of utilisation compared to the poor efficiency (11 per cent) of burning dung cakes directly.

Several thousand biogas plants have been constructed in developing countries. A screening of the literature indicates that the experience of pioneering individuals and organisations has been the guiding principle rather than a defined scientific approach. Several basic chemical, microbiological, engineering, and social problems have to be tackled to ensure the large-scale adoption of biogas plants, with the concomitant assurances of economic success and cultural acceptance.

Various experiences suggest that efficiency in operation needs to be developed, and some important factors are: reduction in the use of steel in current gas plant designs; optimum design of plants, efficient burners, heating of digesters with solar radiation, coupling of biogas systems with other non-conventional energy sources, design of large-scale community plants, optimum utilisation of digested slurry, microbiological conversion of $CO_2$ to $CH_4$, improvement of the efficiency of digestion of dung and other cellulosic material through enzyme action and other predigestion methods, and anaerobic digestion of urban wastes.

### 17.7.3 Research and development

We may summarise some of the research and development tasks that need to be undertaken as follows.

#### *In basic research*

1. Studies on the choice, culture, and management of the micro-organisms involved in the generation of methane.
2. Studies on bacterial behaviour and growth in the simulated environment of a digester (fermentation components: rate, yield of gas, composition of gas as a function of variables— pH, temperature, agitation—with relation to substrates—manure, algae, water hyacinths).

#### *In applied research*

1. Studies on improving biogas reactor design and economics focusing on: alternative construction materials instead of steel and cement; seeding devices; gas purification methods; auxiliary heating systems; insulator materials; development of appropriate appliances for efficient biogas utilisation (e.g. burners, lamps, mini tractors, etc.).

2. Studies for determining and increasing the traditionally acknowledged fertiliser value of sludge.
3. Studies on quicker dewatering of sludge.
4. Studies on deployment of methane to strengthening small-scale industries, e.g. brick-making, welding, etc.

### *In social research*

1. Effective deployment of the written, spoken, and printed word in overcoming the social constraints to the use of biogas by rural populations.
2. Programs designed to illustrate the benefits accruing to rural household and community hygiene and health.
3. Programs designed to illustrate the need for proper management of rural natural resources and for boosting rural crop yields in counteracting food and feed unavailability and insufficiency.
4. On-site training of extension and technical personnel for fieldwork geared to the construction, operation, maintenance, and servicing of biogas generating systems.
5. Involvement and training of rural administrative and technical personnel in regional, national, and international activities focusing on the potentials and benefits of integrated biogas systems.

### 17.7.4 Benefits of biogas utilisation

Table 17.4 shows a number of the benefits of biogas utilisation, set against the related drawbacks of presently used alternatives.

## 17.8 Storage and transportation of biogas and biomethane

Dairy manure biogas is generally used in combined heat and power applications (CHP) that combust the biogas to generate electricity and heat for on-farm use. The electricity is typically produced directly from the biogas as it is created, although the biogas may be stored for later use when applications require variable power or when production is greater than consumption.

Biogas that has been upgraded to biomethane by removing the $H_2S$, moisture, and $CO_2$ can be used as a vehicular fuel. Since production of such fuel typically exceeds immediate on-site demand, the biomethane must be stored for future use, usually either as compressed biomethane (CBM) or liquefied biomethane (LBM). Because most farms will produce more biomethane than they can use on-site, the excess biomethane must be transported to a location where it can be used or further distributed.

This section discusses the types of systems available for the storage of biogas and/or biomethane as well as modes of biomethane transportation.

**Table 17.4** Benefits of biogas utilisation.

| Present problems | Benefits of biogas |
|---|---|
| Depletion of forests for firewood and causation of ecological imbalance and climatic changes | Positive impact on deforestation; relieves a portion of the labour force from having to collect wood and transport coal; helps conserve local energy resources |
| Burning of dung cakes: source of environmental pollution; decreases inorganic nutrients; night soil transportation a hazard to health | Inexpensive solution to problem of rural fuel shortage; improvements in the living and health standards of rural and village communities; provides employment opportunities in spin-off small-scale industries |
| Untreated manure, organic wastes, and residues lost as valuable fertiliser | Residual sludge is applied as top-dressing; good soil conditioner; inorganic residue useful for land reclamation |
| Untreated refuse and organic wastes a direct threat to health | Effective destruction of intestinal pathogens and parasites; end-products non-polluting, cheap; odours non-offensive |
| Initial high cost resulting from installation, maintenance, storage, and distribution costs of end-products | System pays for itself |
| Social constraints and psychological prejudice to use of human waste materials | Income-generator and apt example of self-reliance and self-sufficiency |

### 17.8.1 Storage systems and costs

There are two basic reasons for storing biogas or biomethane: storage for later on-site usage and storage before and/or after transportation to off-site distribution points or systems. The least expensive and easiest to use storage systems for on-farm applications are low-pressure systems; these systems are commonly used for on-site, intermediate storage of biogas. The energy, safety, and scrubbing requirements of medium- and high-pressure storage systems make them costly and high-maintenance options for on-farm use. Such extra costs can be best justified for biomethane, which has a higher heat content and is therefore a more valuable fuel than biogas.

## Biogas storage

Both biogas and biomethane can be stored for on-farm uses. In practice, however, most biogas is used as it is produced. Thus, the need for biogas storage is usually of a temporary nature, at times when production exceeds consumption or during maintenance of digester equipment. Important considerations for on-farm storage of biogas include: (i) the needed volume (typically, only small amounts of biogas need to be stored at any one time), (ii) possible corrosion from $H_2S$ or water vapour that may be present, even if the gas has been partially cleaned, and (iii) cost (since biogas is a relatively low-value fuel).

*(a) Low-pressure storage of biogas*

Floating gas holders on the digester form a low-pressure storage option for biogas systems. These systems typically operate at pressures up to 10-inch water column (less than 2 psi). Floating gas holders can be made of steel, fibreglass, or a flexible fabric. A separate tank may be used with a floating gas holder for the storage of the digestate and also storage of the raw biogas. One advantage of a digester with an integral gas storage component is the reduced capital cost of the system. The least expensive and most trouble-free gas holder is the flexible inflatable fabric top, as it does not react with the $H_2S$ in the biogas and is integral to the digester. These types of covers are often used with plug-flow and complete-mix digesters. Flexible membrane materials commonly used for these gas holders include high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low density polyethylene (LLDPE), and chlorosulphonated polyethylene covered polyester (such as Hypalon®, a registered product of DuPont Dow Elastomers LLC). Thicknesses for cover materials typically vary from 18 to 100 mils (0.5 to 2.5 millimetres). In addition, gas bags of varying sizes are available and can be added to the system. These bags are manufactured from the same materials mentioned above and may be protected from puncture damage by installing them as liners for steel or concrete tanks.

*(b) Medium-pressure storage of cleaned biogas*

Biogas can also be stored at medium pressure between 2 and 200 psi, although this is rarely, if ever done, in the USA. To prevent corrosion of the tank components and to ensure safe operation, the biogas must first be cleaned by removing $H_2S$. Next, the cleaned biogas must be slightly compressed prior to storage in tanks. Typical propane gas tanks are rated to 250 psi. Compressing biogas to this pressure range uses about 5 kWh per 1000 $ft^3$.

Assuming the biogas is 60 per cent methane and a heat rate of 13,600 Btu/kWh, the energy needed for compression is approximately 10 per cent of the energy content of the stored biogas.

## Biomethane storage

Biomethane is less corrosive than biogas and also is potentially more valuable as a fuel. For these reasons, it may be both possible and desirable to store biomethane for on- or off-farm uses.

*(a) High-pressure storage of compressed biomethane*

Biomethane can be stored as CBM to save space. Gas scrubbing is even more important at high pressures because impurities such as $H_2S$ and water are very likely to condense and cause corrosion. The gas is stored in steel cylinders such as those typically used for storage of other commercial gases. Storage facilities must be adequately fitted with safety devices such as rupture disks and pressure relief valves. The cost of compressing gas to high pressures between 2000 and 5000 psi is much greater than the cost of compressing gas for medium-pressure storage. Because of these high costs, the biogas is typically upgraded to biomethane, a more valuable product, prior to compression. Compression to 2000 psi requires nearly 14 kWh per 1000 ft of biomethane. If the biogas is upgraded to 97 per cent methane and the assumed heat rate is 12,000 Btu/kWh, the energy needed for compression amounts to 17 per cent of the energy content of the gas. The main components of an example on-farm CBM storage system are shown in Fig. 17.5. The low-pressure storage tank is a buffer for the output from the biogas upgrading equipment. The tank would most likely consist of one or two large, air-tight vessels with sufficient storage capacity for around one to two days worth of biogas production. For example, a dairy with 1000 cows would yield approximately 30,000 $ft^3$ biomethane/day. Note that by compressing the biomethane slightly, the amount of gas stored in the low-pressure storage tank can be increased proportionately. Large, stationary low-pressure storage tanks suitable for this application are typically custom designed and are available from many manufacturers.

Because it is highly unlikely that there would be sufficient on-farm vehicle demand for all of the biomethane that a farm could produce, most or all of the biomethane must eventually be transported to a refuelling station. Biomethane has an inherently low energy density at atmospheric pressure; therefore, the most economical and efficient way to transport upgraded biogas over the road is in compressed form. Since CNG refuelling stations normally provide CNG at 3000 to 3600 psi, CBM would be transported at similar or higher pressures to minimise the need for additional compression at the refuelling station. The compressor receives the low-pressure biomethane from the storage tank and compresses it to 3600 to 5000 psi. The compressor should be specified to handle the output flow rate from the biogas upgrading equipment. For example, a dairy with 1000 cows would yield a flow rate of approximately 2000 $ft^3$ raw biogas/hour.

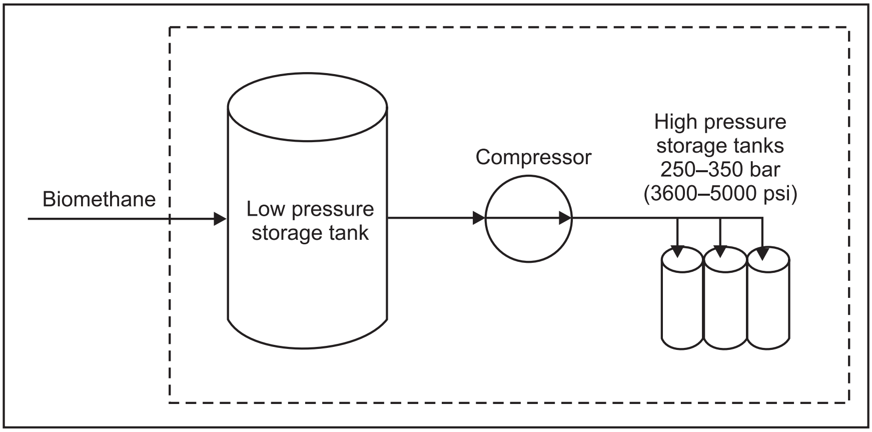



**Figure 17.5** Schematic of on-farm storage system for compressed biomethane

The CBM output of the compressor is fed to a number of individual high-pressure storage tanks connected in parallel and housed in a portable trailer. (In the case of on-farm CBM refuelling, the high-pressure storage tanks could be stationary and potentially much larger.) Portable high-pressure storage tanks rated for this type of application are commercially available from a variety of manufacturers.

## *Storage of liquefied biomethane*

Biomethane can also be liquefied, creating a product known as liquefied biomethane (LBM). Two of the main advantages of LBM are that it can be transported relatively easily and it can be dispensed to either LNG vehicles or CNG vehicles (the latter is made possible through a liquid-to-compressed natural gas [LCNG] refuelling station equipment which creates CNG from LNG feedstock). However, if LBM is to be used off-farm, it must transported by tanker trucks, which normally have a 10,000-gallon capacity. For obvious economic reasons, the LBM must be stored on-farm until 10,000 gallons have accumulated.

Figure 17.6 shows the generalised process of storing LBM prior to use or transport. The low-pressure storage tank is a buffer for LBM after it exits the biomethane liquefaction equipment. Typical LNG storage tanks are double-walled, thermally insulated vessels with storage capacities of 15,000 gallons for stationary, above ground applications. (Smaller LNG storage tanks with 6000-gallon storage capacities are also available, but would only be useful for on-farm applications, and the on-farm demand for LBM is likely to be relatively low.) For a dairy with 1000 cows, 15,000 gallons is equivalent to approximately six weeks' worth of LBM production. The LBM output of the biogas liquefaction equipment is nominally at 50 psi, which is also the nominal pressure of the LBM in the low-pressure storage tank. LNG storage tanks are available from several companies specialising in LNG equipment.

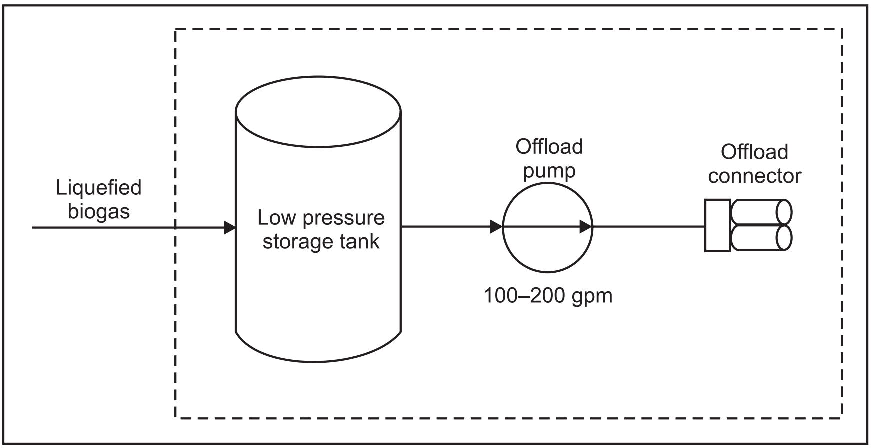



**Figure 17.6** Schematic of storage system for liquefied biomethane

Since it is highly unlikely that on-farm vehicle demand will consume all of the LBM produced, most or all of the LBM must be transported to a refuelling station where it can be dispensed to natural-gas fuelled vehicles. Liquid biomethane is transported in the same manner as LNG, that is, via insulated tanker trucks designed for transportation of cryogenic liquids. Standard tanker trucks hold 10,000 gallons of LNG or LBM at approximately 50 psi. An offload pump is needed to pump the LBM from the low-pressure storage tank to the tanker truck (Fig. 17.6). The offload connector is a standard LNG interface connector and is normally included as part of the offload pump. One of the main disadvantages of LNG and thus LBM is that the cryogenic liquid will heat up during storage, which will result in loss of LBM to evaporation through a release valve on the tank. To minimise these losses, LBM should be used fairly quickly after production. It is generally recommended that LBM be stored for no more than a week before it is either used or transported to a fuelling station. Storage for a longer period will result in an economically unacceptable level of evaporative loss. Since standard LNG tankers carry about 10,000 gallons, a small-scale liquefaction facility should produce at least 3000 gallons of LBM per day. However, the production of this much LBM requires approximately 8000 cows—which could only be found at an extremely large dairy or a central digester facility.

## 17.8.2 Distribution of biomethane

Biogas is a low-grade, low-value fuel and therefore it is not economically feasible to transport it for any distance. Likewise, biogas cannot be economically trucked. In contrast, biomethane can be distributed to its ultimate point of consumption by one of several options, depending on its point of origin:

1. Distribution via dedicated biomethane pipelines
2. Distribution via the natural gas pipeline
3. Over-the-road transport of CBM
4. Over-the-road transport of LBM

### *Distribution via dedicated biomethane pipelines*

If the point of consumption is relatively close to the point of production (e.g. less than 1 mile), the biomethane would typically be distributed via dedicated biogas pipelines (buried or above ground). For example, biomethane intended for use as CNG vehicle fuel could be transported via dedicated pipelines to a CNG refuelling station. For short distances over privately owned property where easements are not required, this is usually the most cost-effective method. Note that biomethane distributed via dedicated biomethane pipelines must compete with natural gas prices in the marketplace.

### *Distribution via the natural gas pipeline network*

The natural gas pipeline network offers a potentially unlimited storage and distribution system for biomethane. Since the natural gas pipelines are typically owned by either private or municipal gas utilities, the biomethane producer must negotiate an agreement with the pipeline owner (i.e. the local gas utility) to supply biomethane into the natural gas pipelines. One prerequisite for such an agreement would be to ensure that biomethane injected into the natural gas pipeline network meets the local gas utility's pipeline gas quality (e.g. gas composition) standards. Once the biomethane is injected into the natural gas pipeline network, it can be used as a direct substitute for natural gas by any piece of equipment connected to the natural gas grid, including domestic gas appliances, commercial/industrial gas equipment, and CNG refuelling stations.

As mentioned, any gas (including biomethane) transported via the natural gas pipeline network is required to meet the local gas company gas quality standards set by the owner of the natural gas pipeline network.

### *Over-the-road transportation of compressed biomethane*

If distribution of biomethane via dedicated pipelines or the natural gas grid is impractical or prohibitively expensive, over-the-road transportation of compressed biomethane may be a distribution option. The energy density of biomethane is extremely low at ambient pressure and as a result it must be compressed to relatively high pressures (e.g. 3000 to 3600 psi) to transport economically in over-the-road vehicles.

Compressed natural gas bulk transport vehicles, often referred to as 'tube trailers', are used when over-the-road transportation of CNG or compressed biomethane is required.

Given the transportation and capital equipment costs associated with over-the-road transportation of compressed biomethane as well as the probable need for additional compression at the point of consumption, this method of biomethane distribution is generally not considered a long-term, cost-effective solution. Rather it is used as a temporary solution in certain situations, for example, as a means of expanding the use of compressed biomethane vehicle fuel into a new market prior to the installation of permanent refuelling infrastructure.

### *Over-the-road transportation of liquefied biomethane*

Over-the-road transportation of liquefied biomethane is a potential way of addressing many of the infrastructure issues associated with biomethane distribution; however, this distribution method presents additional technical challenges. Bulk LNG is transported in LNG tankers. These are typically class 8 vehicles consisting of a tractor towing a 10,000-gallon LNG tanker. Liquid natural gas is transported at relatively low pressures (e.g. 20 to 150 psi), but because it is a cryogenic liquid (i.e. its nominal temperature is –260ºF), it requires special handling.

## 17.9 Biogas plant—technical and environmental considerations

### 17.9.1 Technical considerations

The biogas plant consists of two components: a digester (or fermentation tank) and a gas holder. The digester is a cube-shaped or cylindrical waterproof container with an inlet into which the fermentable mixture is introduced in the form of a liquid slurry. The gas holder is normally an airproof steel container that, by floating like a ball on the fermentation mix, cuts off air to the digester (anaerobiosis) and collects the gas generated. In one of the most widely used designs, the gas holder is equipped with a gas outlet, while the digester is provided with an overflow pipe to lead the sludge out into a drainage pit.

For biogas plant construction, important criteria are: (i) the amount of gas required for a specific use or uses, and (ii) the amount of waste material available for processing.

Digester reactors are constructed from brick, cement, concrete, and steel. In Indonesia, where rural skills in brick making, brick laying, plastering, and bamboo craft are well established, clay bricks have successfully replaced cement blocks and concrete. In areas where the cost is high, the 'sausage' or bag digester appears to be ideal. The digester is constructed of 0.55 mm thick Hypalon laminated with Neoprene and reinforced with nylon. The bag is fitted with an inlet and an outlet made from PVC. Even if imported from the United States, the cost of the digester and the gas holder (both combined in one bag) is only 10 per cent of that for a concrete-steel digester.

Another advantage is that it can be mass produced and is easily mailed. In rural areas, the whole installation is completed in a matter of minutes. A hole in the ground accommodates the bag, which is filled two-thirds full with waste-water. Gas production fully inflates the bag, which is weighted down and fitted with a compressor to increase gas pressure.

## 17.9.2 Environmental and operational considerations

### *Raw materials*

Raw materials may be obtained from a variety of sources—livestock and poultry wastes, night soil, crop residues, food-processing and paper wastes, and materials such as aquatic weeds, water hyacinth, filamentous algae, and seaweed. Different problems are encountered with each of these wastes with regard to collection, transportation, processing, storage, residue utilisation, and ultimate use. Residues from the agricultural sector such as spent straw, hay, cane trash, corn and plant stubble, and bagasse need to be shredded in order to facilitate their flow into the digester reactor as well as to increase the efficiency of bacterial action. Succulent plant material yields more gas than dried matter does, and hence materials like brush and weeds need semi-drying. The storage of raw materials in a damp, confined space for over ten days initiates anaerobic bacterial action that, though causing some gas loss, reduces the time for the digester to become operational.

### Influent solids content

Production of biogas is inefficient if fermentation materials are too dilute or too concentrated, resulting in, low biogas production and insufficient fermentation activity, respectively. Experience has shown that the raw-material (domestic and poultry wastes and manure) ratio to water should be 1:1, i.e. 100 kg of excrete to 100 kg of water. In the slurry, this corresponds to a total solids concentration of 8–11 per cent by weight.

### Loading

The size of the digester depends upon the loading, which is determined by the influent solids content, retention time, and the digester temperature. Optimum loading rates vary with different digesters and their sites of location. Higher loading rates have been used when the ambient temperature is high. In general, the literature is filled with a variety of conflicting loading rates. In practice, the loading rate should be an expression of either: (i) the weight of total volatile solids (TVS) added per day per unit volume of the digester, and (ii) the weight of TVS added per day per unit weight of TVS in the digester. The latter principle is normally used for smooth operation of the digester.

### Seeding

Common practice involves seeding with an adequate population of both the acid-forming and methanogenic bacteria. Actively digesting sludge from a sewage plant constitutes ideal ‘seed’ material. As a general guideline, the seed material should be twice the volume of the fresh manure slurry during the start-up phase, with a gradual decrease in amount added over a three-week period. If the digester accumulates volatile acids as a result of overloading, the situation can be remedied by reseeding or by the addition of lime or other alkali.

### pH

Low pH inhibits the growth of the methanogenic bacteria and gas generation and is often the result of overloading. A successful pH range for anaerobic digestion is 6.0–8.0; efficient digestion occurs at a pH near neutrality. A slightly alkaline state is an indication that pH fluctuations are not too drastic. Low pH may be remedied by dilution or by the addition of lime.

### Temperature

With a mesophilic flora, digestion proceeds best at 30°–40°C; with thermophiles, the optimum range is 50°–60°C. The choice of the temperature to be used is influenced by climatic considerations. In general, there is no rule of thumb, but for optimum process stability, the temperature should be carefully regulated within a narrow range of the operating temperature. In warm climates, with no freezing temperatures, digesters may be operated without added heat. As a safety measure, it is common practice either to bury the digesters in the ground on account of the advantageous insulating properties of the soil or to use a greenhouse covering. Heating requirements and, consequently, costs, can be minimised through the use of natural materials such as leaves, sawdust, straw, etc. which are composted in batches in a separate compartment around the digester.

### *Nutrients*

The maintenance of optimum microbiological activity in the digester is crucial to gas generation and consequently is related to nutrient availability. Two of the most important nutrients are carbon and nitrogen and a critical factor for raw material choice is the overall C/N ratio.

Domestic sewage and animal and poultry wastes are examples of N-rich materials that provide nutrients for the growth and multiplication of the anaerobic organisms. On the other hand, N-poor materials like green grass, corn stubble, etc. are rich in carbohydrate substances that are essential for gas production. Excess availability of nitrogen leads to the formation of $NH_3$, the concentration of which inhibits further growth. Ammonia toxicity can be remedied by low loading or by dilution. In practice, it is important to maintain, by weight, a C/N ratio close to 30:1 for achieving an optimum rate of digestion. The C/N ratio can be judiciously manipulated by combining materials low in carbon with those that are high in nitrogen, and vice versa.

### *Toxic materials*

Wastes and biodegradable residue are often accompanied by a variety of pollutants that could inhibit anaerobic digestion. Potential toxicity due to ammonia can be corrected by remedying the C/N ratio of manure through the addition of shredded bagasse or straw or by dilution. Common toxic substances are the soluble salts of copper, zinc, nickel, mercury, and chromium. On the other hand, salts of sodium, potassium, calcium, and magnesium may be stimulatory or toxic in action, both manifestations being associated with the cation rather than the anionic portion of the salt. Pesticides and synthetic detergents may also be troublesome to the process.

### *Stirring*

When solid materials not well shredded are present in the digester, gas generation may be impeded by the formation of a scum that is comprised of these low-density solids that are enmeshed in a filamentous matrix. In time the scum hardens, disrupting the digestion process and causing stratification. Agitation can be done either mechanically with a plunger or by means of rotational spraying of fresh influent. Agitation, normally required for bath digesters, ensures exposure of new surfaces to bacterial action, prevents viscid stratification and slow-down of bacterial activity, and promotes uniform dispersion of the influent materials throughout the fermentation liquor, thereby accelerating digestion.

### *Retention time*

Other factors such as temperature, dilution, loading rate, etc. influence retention time. At high temperature biodigestion occurs faster, reducing the time requirement. A normal period for the digestion of dung would be two to four weeks.

# 18
# Biomass gasification

## 18.1 Introduction

Modern agriculture is an extremely energy intensive process. However, high agricultural productivities and subsequently the growth of green revolution has been made possible only by large amount of energy inputs, especially those from fossil fuels. With recent price rise and scarcity of these fuels, there has been a trend towards use of alternative energy sources like solar, wind, geothermal, etc. However these energy resources have not been able to provide an economically viable solution for agricultural applications.

One biomass energy-based system, which has been proven reliable and had been extensively used for transportation and on farm systems during World War II, is wood or biomass gasification.

Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of carbon monoxide (CO), hydrogen ($H_2$) and traces of methane ($CH_4$). This mixture is called producer gas. Producer gas can be used to run internal combustion engines (both compression and spark ignition), can be used as substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol—an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel.

Besides, there is a problem that solid wastes (available on the farm) are seldom in a form that can be readily utilised economically, e.g. wood wastes can be used in hog fuel boiler but the equipment is expensive and energy recovery is low. As a result it is often advantageous to convert this waste into more readily usable fuel from like producer gas; hence, the attractiveness of gasification.

However, under present conditions, economic factors seem to provide the strongest argument of considering gasification. In many situations where the price of petroleum fuels is high or where supplies are unreliable the biomass gasification can provide an economically viable system—provided the suitable biomass feedstock is easily available (as is indeed the case in agricultural systems).

The production of generator gas (producer gas) called gasification, is partial combustion of solid fuel (biomass) and takes place at temperatures of about 1000°C. The reactor is called a gasifier.

The combustion products from complete combustion of biomass generally contain nitrogen, water vapour, carbon dioxide and surplus of oxygen. However, in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are (Fig. 18.1) combustible gases like carbon monoxide (CO), hydrogen ($H_2$) and traces of methane and useless products like tar and dust. The production of these gases is by reaction of water vapour and carbon dioxide through a glowing layer of charcoal. Thus the key to gasifier design is to create conditions such that (i) biomass is reduced to charcoal, and (ii) charcoal is converted at suitable temperature to produce CO and $H_2$.

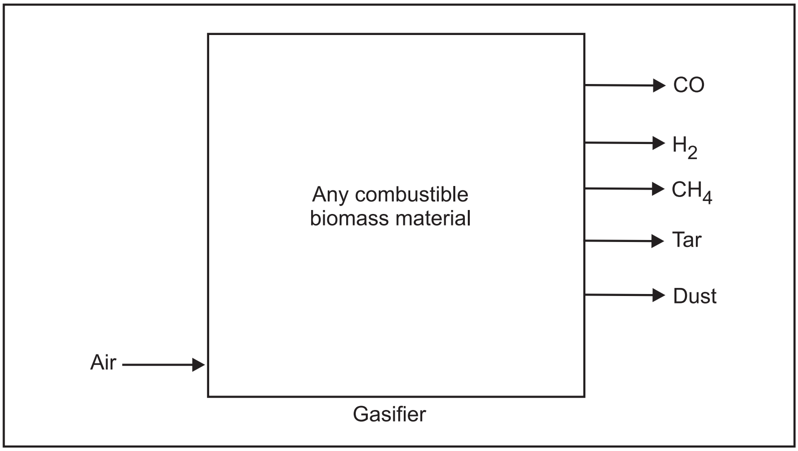



**Figure 18.1** Products of gasification

## 18.2 Types of gasifiers

Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced in it. There are three types of gasifiers (Fig. 18.2): downdraft, updraft and crossdraft. And as the classification implies, updraft gasifier has air passing through the biomass from bottom and the combustible gases come out from the top of the gasifier. Similarly in the downdraft gasifier, the air is passed from the tuyers in the downdraft direction. With slight variation almost all the gasifiers fall in the above categories.

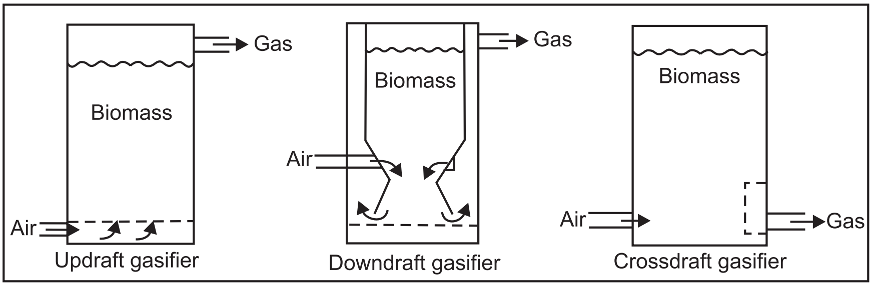



**Figure 18.2** Various types of gasifiers

The choice of one type of gasifier over other is dictated by the fuel, its final available form, its size, moisture content and ash content. Table 18.1 lists, therefore, the advantages and disadvantages generally found for various classes of gasifiers.

**Table 18.1** Advantages and disadvantages of various gasifiers.

| Gasifier type | Advantage | Disadvantages |
|---|---|---|
| Updraft | Small pressure drop | Great sensitivity to tar and moisture and moisture content of fuel |
| | Good thermal efficiency | Relatively long time required for start up of IC engine |
| | Little tendency towards slag formation | Poor reaction capability with heavy gas load |
| Downdraft | Flexible adaptation of gas production to load | Design tends to be tall |
| | Low sensitivity to charcoal dust and tar content of fuel | Not feasible for very small particle size of fuel |
| Crossdraft | Short design height | Very high sensitivity to slag formation |
| | Very fast response time to load | High pressure drop |
| | Flexible gas production | |

## 18.2.1 Process zones

Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are as follows:

1. Drying of fuel
2. Pyrolysis—a process in which tar and other volatiles are driven off
3. Combustion
4. Reduction

Though there is a considerable overlap of the processes, each can be assumed to occupy a separate zone where fundamentally different chemical and thermal reactions take place. Figure 18.3 shows schematically an updraft gasifier with different zones and their respective temperatures. Figures 18.4 and 18.5 show these regions for downdraft and crossdraft gasifiers, respectively.

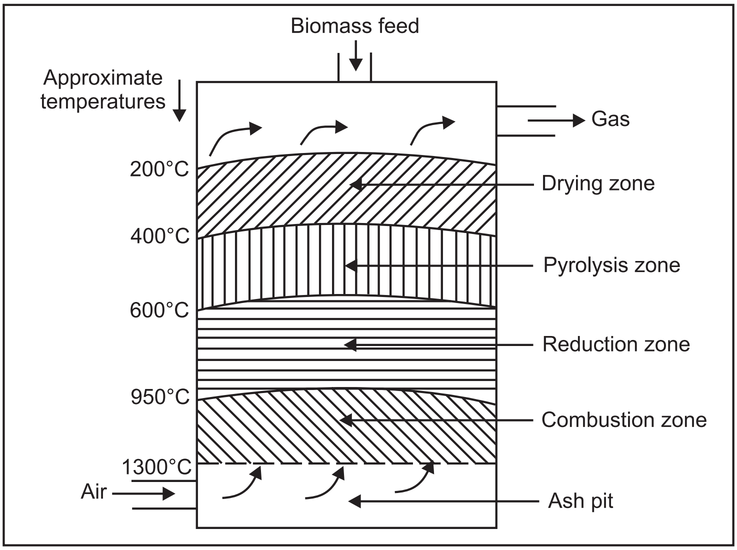



**Figure 18.3** Various zones in updraft gasifier

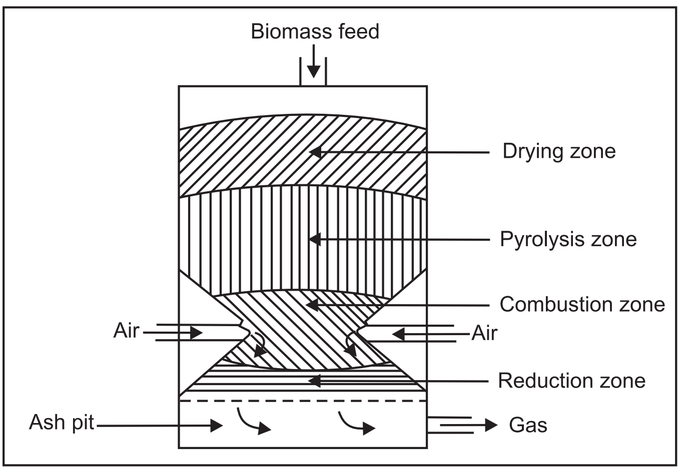



**Figure 18.4** Gasification process is downdraft gasifier

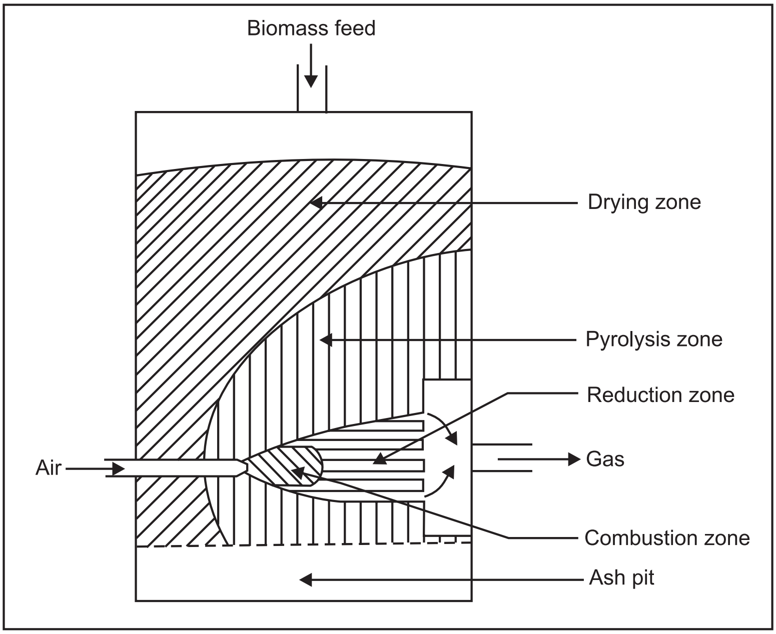



**Figure 18.5** Gasification process is crossdraft gasifier

In the downdraft gasifiers, there are two types: (i) single throat, and (ii) double throat (Fig. 18.6).

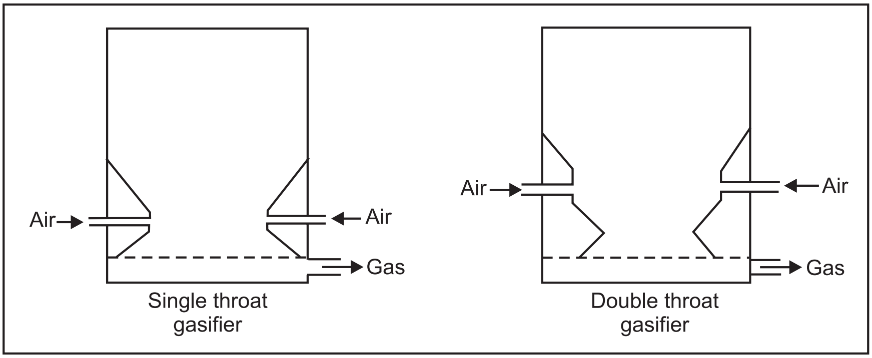



**Figure 18.6** Single and double throat gasifier

Single throat gasifiers are mainly used for stationary applications, whereas double throat are for varying loads as well as automotive purposes.

## 18.2.2 Reaction chemistry

The following major reactions take place in combustion and reduction zone.

### *Combustion zone*

The combustible substance of a solid fuel is usually composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and water is obtained from the hydrogen, usually as steam. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1450°C. The main reactions, therefore, are

$$C + O_2 = CO_2 \text{ (+393 MJ/kg mole)} \quad \text{... (18.1)}$$

$$2H_2 + O_2 = 2H_2O \text{ (–242 MJ/kg mole)} \quad \text{... (18.2)}$$

### *Reaction zone*

The products of partial combustion (water, carbon dioxide and uncombusted partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the following reduction reactions take place.

$$C + CO_2 = 2CO \text{ (–164.9 MJ/kg mole)} \quad \text{... (18.3)}$$

$$C + H_2O = CO + H_2 \text{ (–122.6 MJ/kg mole)} \quad \text{... (18.4)}$$

$$CO + H_2O = CO + H_2 \text{ (+ 42 MJ/kg mole)} \quad \text{... (18.5)}$$

$$C + 2H_2 = CH_4 \text{ (+ 75 MJ/kg mole)} \quad \text{... (18.6)}$$

$$CO_2 + H_2 = CO + H_2O \text{ (–42.3 MJ/kg mole)} \quad \text{... (18.7)}$$

Equations 18.3 and 18.4 are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently, the temperatures in the reduction zone are normally 800–1000°C. Lower the reduction zone temperature (~700–800°C), lower is the calorific value of gas.

### *Pyrolysis zone*

Wood pyrolysis is an intricate process that is still not completely understood. The products depend upon temperature, pressure, residence time and heat losses. However following general remarks can be made about them.

Up to the temperature of 200°C only water is driven off. Between 200° and 280°C carbon dioxide, acetic acid and water are given off. The real pyrolysis, which takes place between 280° and 500°C, produces large quantities of tar and gases containing carbon dioxide. Besides light tars, some methyl alcohol is also formed. Between 500° and 700°C the gas production is small and contains hydrogen.

Thus it is easy to see that updraft gasifier will produce much more tar than downdraft one. In downdraft gasifier the tars have to go through combustion and reduction zone and are partially broken down.

Since majority of fuels like wood and biomass residue do have large quantities of tar, downdraft gasifier is preferred over others. Indeed majority of gasifiers, both in World War II and presently, are of downdraft type.

Finally in the drying zone the main process is of drying of wood. Wood entering the gasifier has moisture content of 10–30 per cent. Various experiments on different gasifiers in different conditions have shown that on an average the condensate formed is 6–10 per cent of the weight of gasified wood. Some organic acids also come out during the drying process. These acids give rise to corrosion of gasifiers.

## 18.2.3 Properties of producer gas

The producer gas is affected by various processes as outlined above; hence, one can expect variations in the gas produced from various biomass sources. Table 18.2 lists the composition of gas produced from various sources. The gas composition is also a function of gasifier design and thus, the same fuel may give different calorific value as when used in two different gasifiers. Table 18.2 therefore shows approximate values of gas from different fuels.

**Table 18.2** Composition of producer gas from various fuels.

| Fuel | Gasification method | Volume percentage | | | | | Calorific value MJ/m$^3$ |
|---|---|---|---|---|---|---|---|
| | | CO | $H_2$ | $CH_4$ | $CO_2$ | $N_2$ | |
| Charcoal | Downdraft | 28–31 | 5–10 | 1–2 | 1–2 | 55–60 | 4.60–5.65 |
| Wood with 12–20% moisture content | Downdraft | 17–22 | 16–20 | 2–3 | 10–15 | 55–50 | 5.00–5.86 |
| Wheat straw pellets | Downdraft | 14–17 | 17–19 | – | 11–14 | – | 4.50 |
| Coconut husks | Downdraft | 16–20 | 17–19.5 | – | 10–15 | – | 5.80 |
| Coconut shells | Downdraft | 19–24 | 10–15 | – | 11–15 | – | 7.20 |
| Pressed sugarcane | Downdraft | 15–18 | 15–18 | – | 12–14 | – | 5.30 |
| Charcoal | Updraft | 30 | 19.7 | – | 3.6 | 46 | 5.98 |
| Corn cobs | Downdraft | 18.6 | 16.5 | 6.4 | – | – | 6.29 |
| Rice hulls pelleted | Downdraft | 16.1 | 9.6 | 0.95 | – | – | 3.25 |
| Cotton stalks cubed | Downdraft | 15.7 | 11.7 | 3.4 | – | – | 4.32 |

The maximum dilution of gas takes place because of presence of nitrogen. Almost 50–60 per cent of gas is composed of non-combustible nitrogen. Thus it may be beneficial to use oxygen instead of air for gasification. However the cost and availability of oxygen may be a limiting factor in this regard. Nevertheless where the end product is methanol—a high energy quality item, then the cost and use of oxygen can be justified.

On an average 1 kg of biomass produces about 2.5 $m^3$ of producer gas at standard temperature and pressure (STP). In this process it consumes about 1.5 $m^3$ of air for combustion. For complete combustion of wood about 4.5 $m^3$ of air is required. Thus biomass gasification consumes about 33 per cent of theoretical stoichiometric ratio for wood burning.

The average energy conversion efficiency of wood gasifiers is about 60–70 per cent and is defined as:

$$\eta_{\text{Gas}} = \frac{\text{Calorific value of gas/kg of fuel}}{\text{Average calorific value of 1 kg of fuel}} \qquad \text{... (18.8)}$$

*Example:*

1 kg of wood produces 1.5 $m^3$ of gas with average calorific value of 5.4 MJ/$m^3$. Average calorific value of wood (dry) is 19.8 MJ/kg.

Hence:

$$\eta_{\text{Gas}} = \frac{2.5\,(\text{m}^3) \times 5.4(\text{MJ/m}^3)}{19.80\,(\text{MJ/kg}) \times 1(\text{kg})} \qquad \text{... (18.9)}$$

### 18.2.4 Temperature of gas

On an average the temperature of gas leaving the gasifier is about 300–400°C. If the temperature is higher than this (~50°C), it is an indication that partial combustion of gas is taking place. This generally happens when the air flow rate through the gasifier is higher than the design value.

## 18.3 Gasifier fuel characteristics

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20–40 per cent stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated and fuel processing done.

Many gasifier manufacturers claim that a gasifier is available which can gasify any fuel. There is no such thing as a universal gasifier. A gasifier is very fuel specific and it is tailored around a fuel rather than the other way round.

Thus a gasifier fuel can be classified as good or bad according to the following parameters:

1. Energy content of the fuel
2. Bulk density
3. Moisture content
4. Dust content
5. Tar content
6. Ash and slagging characteristic

## 18.3.1 Energy content and bulk density of fuel

The higher the energy content and bulk density of fuel, the similar is the gasifier volume since for one charge one can get power for longer time.

## 18.3.2 Moisture content

In most fuels there is very little choice in moisture content since it is determined by the type of fuel, its origin and treatment. It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable and the heat budget of the gasification reaction is impaired. For example, for fuel at 25°C and raw gas exit temperature from gasifier at 300°C, 2875 kJ/kg moisture must be supplied by fuel to heat and evaporate moisture.

Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pretreatment of fuel is required. Generally desirable moisture content for fuel should be less than 20 per cent.

## 18.3.3 Dust content

All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than 2–6 g/m$^3$ of dust. Figure 18.7 shows dust produced as a function of gas production for wood generators used during World War II.

The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance.

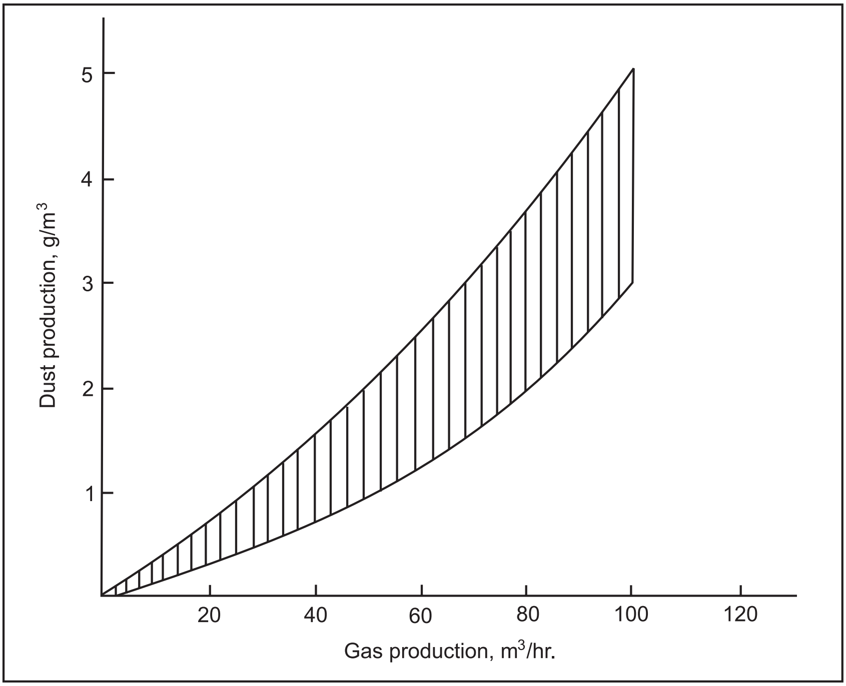



**Figure 18.7** Dust content as a function of gas production

## 18.3.4 Tar content

Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburettor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60 per cent water) to black and highly viscous (7 per cent water). There are approximately 200 chemical constituents that have been identified in tar so far. Very little research work has been done in the area of removing or burning tar in the gasifier so that relatively tar free gas comes out. Thus the major effort has been devoted to cleaning this tar by filters and coolers. A well-designed gasifier should put out less than 1 g/m$^3$ of tar. Usually it is assumed that a downdraft gasifier produces less tar than other gasifiers. However because of localised inefficient processes taking place in the throat of the downdraft gasifier, it does not allow the complete dissociation of tar. More research effort is therefore needed in exploring the mechanism of tar breakdown in downdraft gasifiers.

### 18.3.5 Ash and slagging characteristics

The mineral content in the fuel that remains in oxidised form after complete combustion is usually called ash. The ash content of a fuel and the ash composition have a major impact on trouble free operation of gasifier.

Ash basically interferes with gasification process in two ways:

1. It fuses together to form slag and this clinker stops or inhibits the downward flow of biomass feed.
2. Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel's reaction response.

Ash and tar removal are the two most important processes in gasification system for its smooth running. Various systems have been devised for ash removal. In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier.

Slagging, however, can be overcome by two types of operation of gasifier:

1. Low temperature operation that keeps the temperature well below the flow temperature of the ash.
2. High temperature operation that keeps the temperature above the melting point of ash.

The first method is usually accomplished by steam or water injection while the latter method requires provisions for tapping the molten slag out of the oxidation zone. Each method has its advantages and disadvantages and depends on specific fuel and gasifier design.

Keeping in mind the above characteristics of fuel, only two fuels have been thoroughly tested and proven to be reliable. They are charcoal and wood. They were the principal fuels during World War II and the European countries had developed elaborate mechanisms of ensuring strict quality control on them.

Charcoal, specifically, because of being tar free and having relatively low ash content property was the preferred fuel during World War II and still remains so. However there is a major disadvantage of charcoal in terms of energy. Charcoal is mostly produced from wood and in conversion of wood to charcoal about 50 per cent of original energy is lost. When made by pit method (as is normally made in most developing countries) the losses can be as high as 80 per cent. Besides with the present energy crisis where most countries do not have enough supply of wood it is advantageous and attractive to use agricultural residues. For the agricultural sector this is an extremely attractive alternative.

Many agricultural residues and fuels have, therefore, been gasified. However the operating experience is very limited and most of the work has been on laboratory scale.

## 18.4 Gasification systems

The combustible gases from the gasifier can be used (i) in internal combustion engines, (ii) for direct heat applications, and (iii) as feedstock for production of chemicals like methanol.

However in order for the gas to be used for any of the above applications it should be cleaned of tar and dust and be cooled. As previously mentioned cooling and cleaning of the gas is one of the most important processes in the whole gasification system. The failure or the success of producer gas units depends completely on their ability to provide a clean and cool gas to the engines or for burners. Thus the importance of cleaning and cooling systems cannot be overemphasised.

### 18.4.1 Cooling and cleaning of gas

The temperature of gas coming out of generator is normally between 300°C and 500°C. This gas has to be cooled in order to raise its energy density. Various types of cooling equipment have been used to achieve this end. Most coolers are gas to air heat exchangers where the cooling is done by free convection of air on the outside surface of heat exchanger. Since the gas also contains moisture and tar, some heat exchangers provide partial scrubbing of gas. Thus ideally the gas going to an internal combustion engine should be cooled to nearly ambient temperature.

Cleaning of the gas is trickier and is very critical. Normally three types of filters are used in this process. They are classified as dry, moist and wet. In the dry category are cyclone filters. They are designed according to the rate of gas production and its dust content. The cyclone filters are useful for particle size of 5 μm and greater. Since 60–65 per cent of the producer gas contains particles above 60 μm in size the cyclone filter is an excellent cleaning device. After passing through cyclone filter, the gas still contains fine dust, particles and tar. It is further cleaned by passing through either a wet scrubber or dry cloth filter. In the wet scrubber the gas is washed by water in counter current mode. The scrubber also acts like a cooler, from where the gas goes to cloth or cork filter for final cleaning.

Since cloth filter is a fine filter, any condensation of water on it stops the gas flow because of increase in pressure drop across it. Thus in quite a number of gasification systems the hot gases are passed through the cloth filter and then only do they go to the cooler. Since the gases are still above dew point, no condensation takes place in filter. Figure 18.8 shows schematically a downdraft gasification system with cleaning and cooling train.

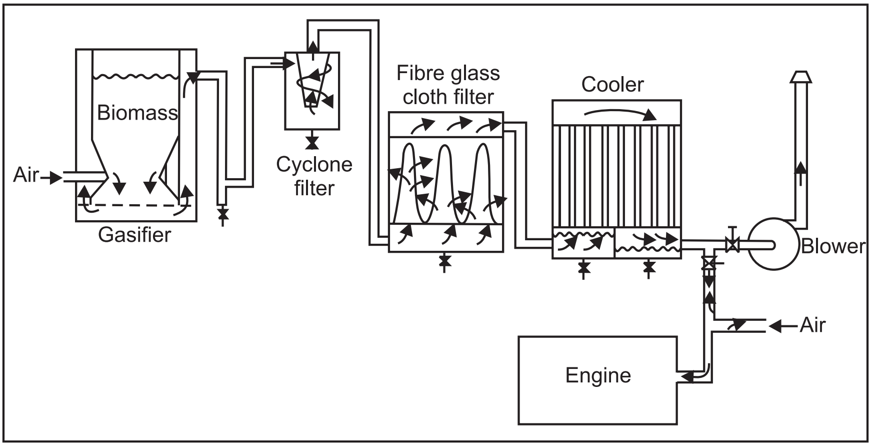



**Figure 18.8** Schematic of producer gas plant

There is quite a substantial pressure drop across the whole gasification system and the design is usually done such that the pressure drop should not exceed 100 cm of water.

## 18.4.2 Shaft power systems

The biggest application of producer gas has been in driving IC engines. Both spark ignition and compression ignition engines have been driven by it. In principle any IC engine can be converted to run completely or partly on the gas. However in actual practice running the engines uninterrupted and for long periods of time without any problem is difficult to achieve.

The trend at present is therefore, to use available IC engines and run them on producer gas. However since the producer gas plant is tailor-made for a specific engine it is worthwhile to look at the engine itself. Producer gas being a relatively low energy gas has certain combustion characteristics that differ markedly from gasoline or diesel oil. Thus in future R&D in gasification it is worthwhile to do considerable work to make an engine specific for the gas. At present no such engine exists.

### *Spark ignition engine*

When a spark ignition engine is converted to operation on producer gas it is derated to about 40–50 per cent. The deration is primarily because of low energy density of producer gas. This accounts for about 30 per cent loss of power. The rest is accounted for by the pressure drop in the intake valves and piping. A spark ignition engine on the whole requires very little modification to run on producer gas. Generally depending upon the make of engine (compression ratio and rpm), the ignition timing has to be advanced by about 30–40°C. This is done because of low flame speed of producer gas as compared to gasoline. Thus an engine with 1500–2500 rpm is ideal for producer gas application (Fig. 18.9).

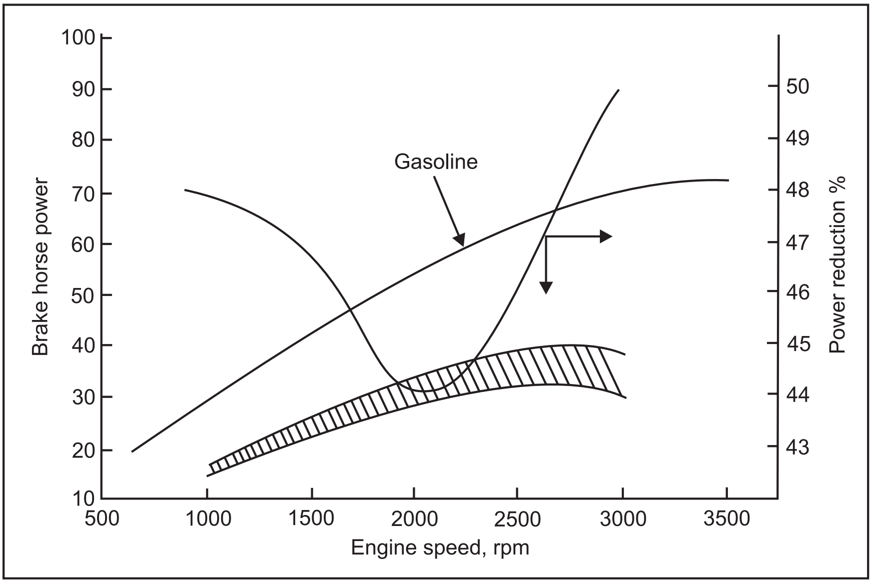



**Figure 18.9** Power reduction as function of engine speed

It should be noted that in general the overall efficiency of the IC engine itself does not change though the power derating takes place. However, detailed comparison of the engine efficiencies with and without producer gas has not been done till now because of insufficient data and large variations in producer gas composition. Thus a conservative figure of 15–20 per cent can be used as efficiency of spark ignition engines.

With the above efficiencies it is easy to calculate the mechanical energy available per kg of biomass gasified. With gasifier efficiency of 68 per cent the total system efficiency (gasification and engine) is 10–13 per cent. Thus on an average one can get 0.55–0.75 kWh of mechanical energy per kilogram of biomass gasified (calorific value of biomass is taken to be 19.6 MJ/kg). This value however changes with the load and can go as low as 0.22 kWh/kg for 10 per cent load to 0.73 kWh/kg for 87 per cent load rated capacity. Nevertheless for purpose of sizing a system, a good number is 0.7 kWh/kg.

### *Compression ignition engine*

A compression ignition or diesel engine cannot be operated on producer gas completely without injection of small amount of diesel. This is because the producer gas cannot ignite by itself under prevailing pressure. Thus for compression ignition engines to run on producer gas, they have to be either: (i) a dual fuel engine, or (ii) converted into spark ignition engines.

Since diesel engines have compression ratio between 16 and 20 and are run at lower rpm than gasoline engines they are ideally suited to run on producer gases with spark ignition. However, conversion of the engine to spark ignition is costly and elaborate affair and the advantages are nullified by the cost.

Thus most of the diesel engines running on producer gas have been dual fuel type. Especially in developing countries, where the proliferation of diesel engines has been because of dual pricing structure (diesel is subsidised).

Because of high compression ratio and low speeds, the derating of diesel engines running on producer gas is only between 15 and 30 per cent. This is far superior to the gasoline engine's derating. Even if gasoline engines are used in dual fuel mode their derating is still between 40 and 50 per cent.

On an average the diesel engine can run on 15–20 per cent (of the original consumption) diesel and rest on producer gas. Generally the engine is started on diesel and as the gas generation builds up the diesel consumption is then kept at the idling level. The engine efficiency in this case is about 25 per cent. Thus as a thumb rule the dual fuel engine producing 1 kWh requires 1 kg of biomass and consumes 0.07 litres of diesel. In both the diesel and gasoline engines the introduction of producer gas to the engine is by a T-valve where, from one section of the T air is sucked in. Thus the complicated carburettor is greatly simplified by the above arrangement. Many arrangements have been developed for introduction of air/gas mixture in the engine.

## 18.4.3 Direct heat systems

Direct heat systems are those in which the producer gas is burnt directly in furnace or boiler. The advantage of this as compared to direct combustion of biomass is in obtaining controlled heating and higher flame temperatures than those obtainable otherwise. Because of direct burning, the gas quality is less critical than is shaft power systems and consequently they are less demanding on cooling and cleaning equipment and have more versatility as far as fuels are concerned.

The direct heat systems have great attraction for agricultural applications like drying of farm produce and consequently may such applications are underway in USA and other countries of the world. Since direct heat systems were rarely used during Second World War, their experience is recent.

Most of the direct heat gasifiers currently available are of updraft or fluidised bed types. Their output range varies from 0.25–25 GJ/hr. Most of these are for large kiln and furnace applications. For agricultural drying purposes their range has to be brought down.

Since the production of gas is uneven and fluctuates with time it is sometimes necessary to have a storage of gas. This can provide very uniform quality gas. However no such systems with storage exist at present.

Because of low energy content of producer gas (~5 MJ/$m^3$) which is about 10–15 per cent that of natural gas, special burners are needed. Since the adiabatic flame temperature of producer gas is about 1400°C. The highest temperature applications can be around 1000–1200°C.

### 18.4.4 Fluidised bed systems

For fuels which have high ash content and the ash has low melting point, fluidised bed combustion seems to gasify them. In fluidised bed gasifiers the air is blown upwards through the biomass bed. The bed under such conditions behaves like boiling fluid and has excellent temperature uniformity and provides efficient contact between gaseous and solid phase. Generally the heat is transferred initially by hot bed of sand. The major advantage of fluidised bed gasifier over, say, downdraft is its flexibility with regard to feed rate and its composition. Fluidised bed systems can also have high volumetric capacity and the temperature can be easily controlled.

However these advantages are offset by the complexity of the system with large blowers for blowing air and augers for feeding biomass. Besides, fluidised bed systems produce more dust and tar as compared to downdraft gasifiers. This puts a heavy load on the cooling and cleaning train. Nevertheless quite a number of research projects are underway to study and optimise biomass residue-based fluidised bed gasification systems. However no large scale manufacturing facility for such systems exists today.

## 18.5 Applications

As was mentioned earlier the main applications of biomass gasifier are:

1. Shaft power systems
2. Direct heat applications
3. Chemical production

In the shaft power systems the main agriculture applications are driving of farm machinery like tractors, harvesters, etc. There are quite a number of manufactures catering to the on-farm machinery gasification systems. Small scale electricity generation systems also provide an attractive alternative to utilities. Another useful application of producer gas units is in irrigation systems. This seems to be the most to be the most important application in developing countries. There is no reason why such systems cannot become popular in developed countries especially when there have been quite a number of solar powered irrigation systems installed.

Direct heat systems, because of their simplicity, may prove to have biggest applications in agriculture. Among them are grain drying, greenhouse heating and running of absorption refrigeration and cooling systems. Again these systems can be coupled to other renewable energy systems like solar for thermal applications. Another interesting application for direct heat (external combustion) application is running of Stirling engines. These engines have very high efficiencies and may prove to be a better alternative than internal combustion engine running on producer gas.

Production of chemicals like methanol and formic acid from producer gas is a recent phenomenon. However with fossil fuels getting scarcer, production of these chemicals by producer gas may prove to be an economically feasible proposition. Another interesting application may be use of producer gas to run a fuel cell plant. The energy density of such a plant would be highly favourable as compared to IC engine systems.

However for all these applications the most important ingredient is the availability of biomass fuel. For on farm applications biomass residues are attractive proposition. However, before any large scale application of gasification is undertaken the fuel availability is to be critically ascertained.

As an example it is instructive to look at the land area required, for a gasifier to run on cotton stalks (biomass residue) as fuel. On an average, quantity of stalks harvested is 1.5 tons/acre/year. Thus a 100 kW gasifier running at 8 hours per day for 300 days/year will require about 213 acres of cotton plantation to produce the required cotton stalks. Against such background all the future applications of gasifiers should be evaluated. If the biomass residue availability is not adequate then the decision has to be made about running it on wood.

However such decisions can only be made at specific sites and for specific applications. Just like in any other alternative energy source it is advisable to use hybrid systems, similarly in biomass gasification systems also it will be worthwhile to use them in conjunction with other energy systems. For example, grain drying can have biomass gasifier/solar coupling. Only in specific cases of methanol or chemical production, should the gasification system be used as separate one.

# 19
# Cogeneration

## 19.1 Introduction

Cogeneration is the simultaneous generation of power and low pressure stream by way of expansion through a turbine. The cogeneration systems have developed a niche for themselves over the conventional. The potential market for cogeneration in industry in future will be influenced by energy prices in India, the economic situation, restructuring tariff regimes and/or the introduction of financial aids. National energy policies could also make the electricity supply industry open for competition.

## 19.2 Need for cogeneration

Thermal power plants are a major source of electricity supply in India. The conventional method of power generation and supply to the customer is wasteful in the sense that only about a third of the primary energy fed into the power plant is actually made available to the user in the form of electricity (Fig. 19.1). In conventional power plant, efficiency is only 35 per cent and remaining 65 per cent of energy is lost. The major source of loss in the conversion process is the heat rejected to the surrounding water or air due to the inherent constraints of the different thermodynamic cycles employed in power generation. Also further losses of around 10–15 per cent are associated with the transmission and distribution of electricity in the electrical grid.

## 19.3 Principle of cogeneration

Cogeneration or combined heat and power (CHP) is defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy. Mechanical energy may be used either to drive an alternator for producing electricity or rotating equipment such as motor, compressor, pump or fan for delivering various services. Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, hot air for dryer or chilled water for process cooling.

Cogeneration provides a wide range of technologies for application in various domains of economic activities. The overall efficiency of energy use in cogeneration mode can be up to 85 per cent and above in some cases.

For example in the scheme shown in Fig. 19.2, an industry requires 24 units of electrical energy and 34 units of heat energy. Through separate heat and power route the primary energy input in power plant will be 60 units (24/0.40). If a separate boiler is used for steam generation then the fuel input to boiler will be 40 units (34/0.85). If the plant had cogeneration then the fuel input will be only 68 units (24 + 34)/0.85 to meet both electrical and thermal energy requirements. It can be observed that the losses, which were 42 units in the case of, separate heat and power has reduced to 10 units in cogeneration mode.

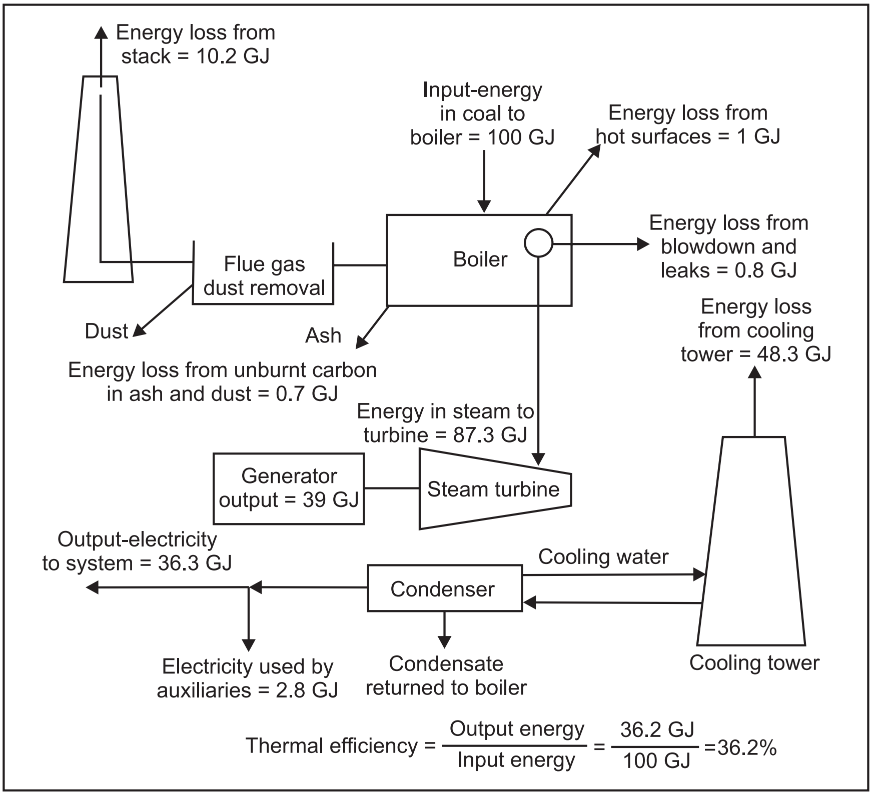



**Figure 19.1** Balance in a typical coal fired power station for an input energy of 100 Giga Joules (GJ)

Along with the saving of fossil fuels, cogeneration also allows to reduce the emission of greenhouse gases (particularly $CO_2$ emission). The production of electricity being on-site, the burden on the utility network is reduced and the transmission line losses eliminated.

Cogeneration makes sense from both macro and micro perspectives. At the macro level, it allows a part of the financial burden of the national power utility to be shared by the private sector; in addition, indigenous energy sources are conserved. At the micro level, the overall energy bill of the users can be reduced, particularly when there is a simultaneous need for both power and heat at the site, and a rational energy tariff is practiced in the country.

## 19.4 Technical options for cogeneration

Cogeneration technologies that have been widely commercialised include extraction/back pressure steam turbines, gas turbine with heat recovery boiler (with or without bottoming steam turbine) and reciprocating engines with heat recovery boiler.

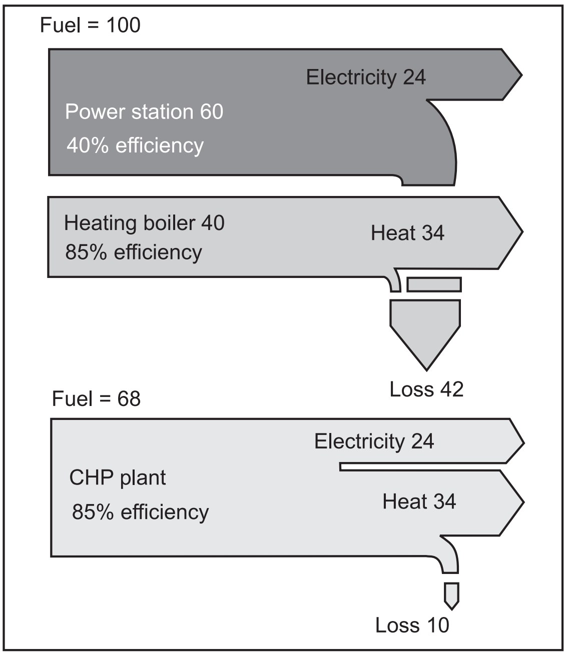



**Figure 19.2** Cogeneration advantage

### 19.4.1 Steam turbine cogeneration systems

The two types of steam turbines most widely used are the backpressure and the extraction-condensing types (Fig. 19.3). The choice between backpressure turbine and extraction-condensing turbine depends mainly on the quantities of power and heat, quality of heat, and economic factors. The extraction points of steam from the turbine could be more than one, depending on the temperature levels of heat required by the processes.

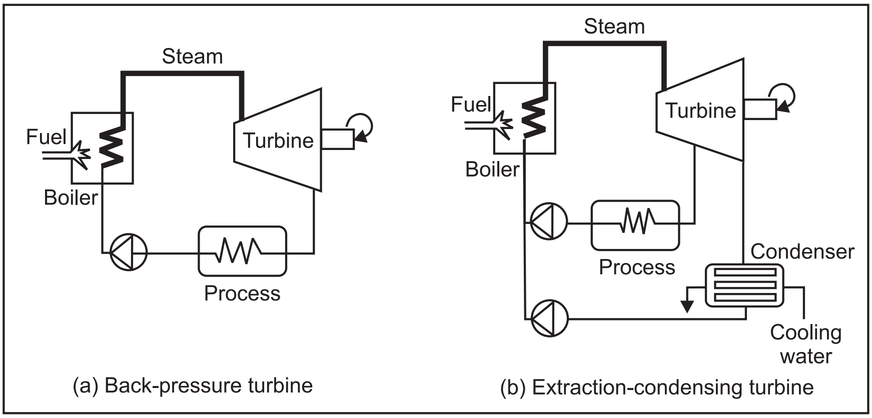



**Figure 19.3** Schematic diagrams of steam turbine cogeneration systems

Another variation of the steam turbine topping cycle cogeneration system is the extraction-back pressure turbine that can be employed where the end-user needs thermal energy at two different temperature levels. The full-condensing steam turbines are usually incorporated at sites where heat rejected from the process is used to generate power.

The specific advantage of using steam turbines in comparison with the other prime movers is the option for using a wide variety of conventional as well as alternative fuels such as coal, natural gas, fuel oil and biomass. The power generation efficiency of the cycle may be sacrificed to some extent in order to optimise heat supply. In backpressure cogeneration plants, there is no need for large cooling towers. Steam turbines are mostly used where the demand for electricity is greater than one MW up to a few hundreds of MW. Due to the system inertia, their operation is not suitable for sites with intermittent energy demand.

### 19.4.2 Gas turbine cogeneration systems

Gas turbine cogeneration systems can produce all or a part of the energy requirement of the site, and the energy released at high temperature in the exhaust stack can be recovered for various heating and cooling applications (Fig. 19.4). Though natural gas is most commonly used, other fuels such as light fuel oil or diesel can also be employed. The typical range of gas turbines varies from a fraction of a MW to around 100 MW.

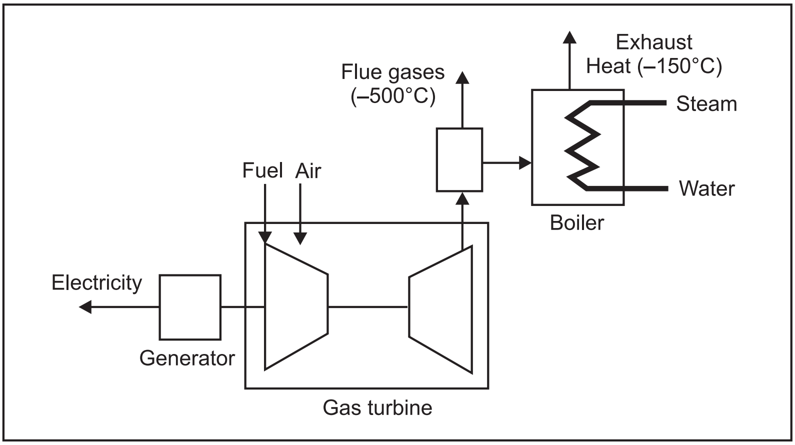



**Figure 19.4** Schematic diagram of gas turbine cogeneration

Gas turbine cogeneration has probably experienced the most rapid development in the recent years due to the greater availability of natural gas, rapid progress in the technology, significant reduction in installation costs, and better environmental performance. Furthermore, the gestation period for developing a project is shorter and the equipment can be delivered in a modular manner. Gas turbine has a short start-up time and provides the flexibility of intermittent operation. Though it has a low heat to power conversion efficiency, more heat can be recovered at higher temperatures. If the heat output is less than that required by the user, it is possible to have supplementary natural gas firing by mixing additional fuel to the oxygen-rich exhaust gas to boost the thermal output more efficiently.

On the other hand, if more power is required at the site, it is possible to adopt a combined cycle that is a combination of gas turbine and steam turbine cogeneration. Steam generated from the exhaust gas of the gas turbine is passed through a backpressure or extraction-condensing steam turbine to generate additional power. The exhaust or the extracted steam from the steam turbine provides the required thermal energy.

### 19.4.3 Reciprocating engine cogeneration systems

Also known as internal combustion (IC) engines, these cogeneration systems have high power generation efficiencies in comparison with other prime movers. There are two sources of heat for recovery: Exhaust gas at high temperature and engine jacket cooling water system at low temperature (Fig. 19.5). As heat recovery can be quite efficient for smaller systems, these systems are more popular with smaller energy consuming facilities, particularly those having a greater need for electricity than thermal energy and where the quality of heat required is not high, e.g. low pressure steam or hot water.

Though diesel has been the most common fuel in the past, the prime movers can also operate with heavy fuel oil or natural gas. These machines are ideal for intermittent operation and their performance is not as sensitive to the changes in ambient temperatures as the gas turbines. Though the initial investment on these machines is low, their operating and maintenance costs are high due to high wear and tear.

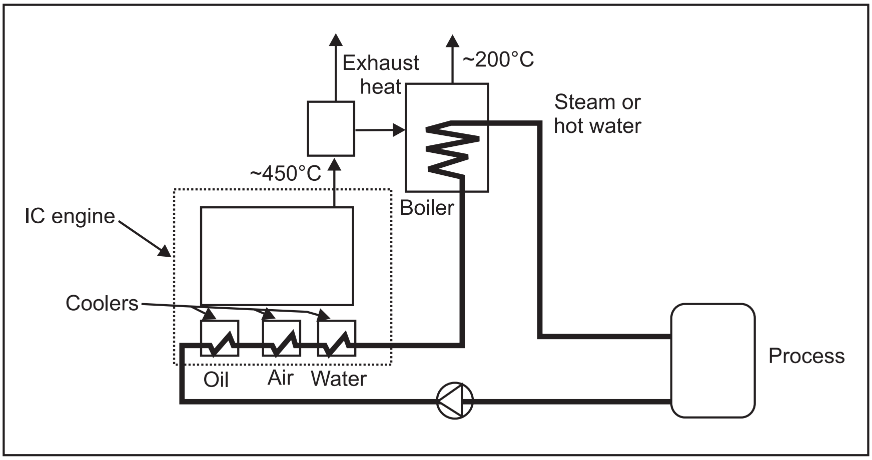



**Figure 19.5** Schematic diagram of reciprocating engine cogeneration

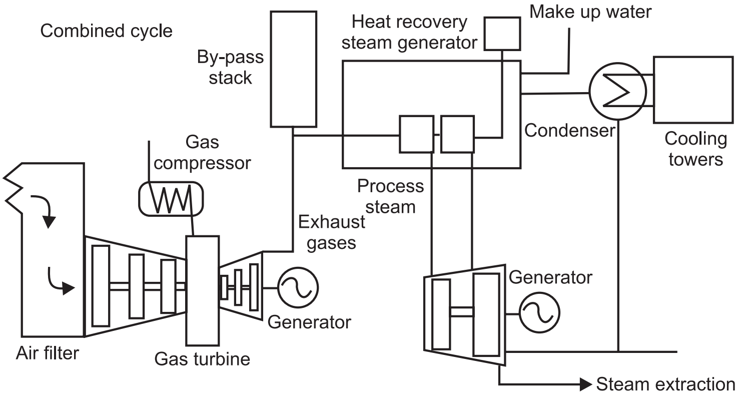
## 19.5 Classification of cogeneration systems

Cogeneration systems are normally classified according to the sequence of energy use and the operating schemes adopted.

A cogeneration system can be classified as either a topping or a bottoming cycle on the basis of the sequence of energy use. In a topping cycle, the fuel supplied is used to first produce power and then thermal energy, which is the by-product of the cycle and is used to satisfy process heat or other thermal requirements. Topping cycle cogeneration is widely used and is the most popular method of cogeneration.

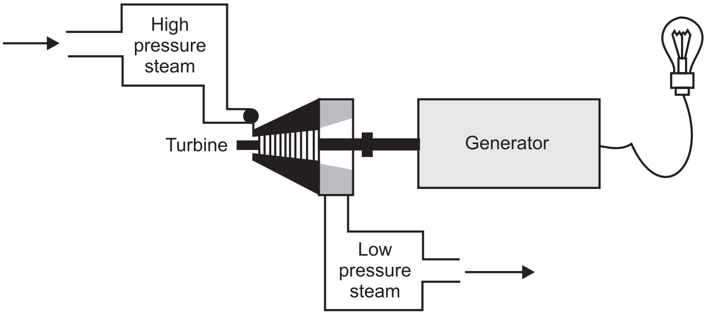
### 19.5.1 Topping cycle

The four types of topping cycle cogeneration systems are briefly explained in Fig. 19.6.



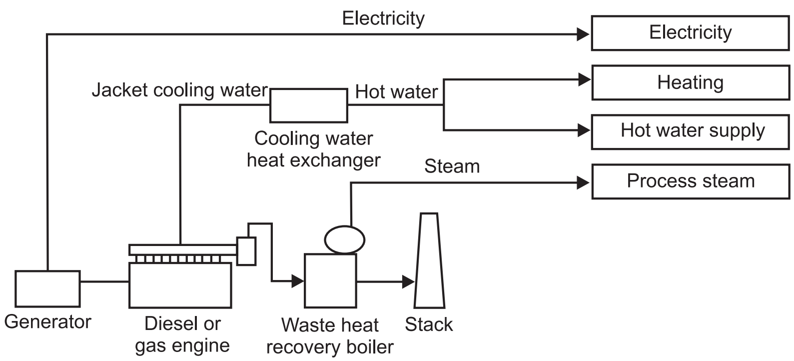

A gas turbine or diesel engine producing electrical or mechanical power followed by a heat recovery boiler to create steam to drive a secondary steam turbine. This is called a combined-cycle topping system.

(a)



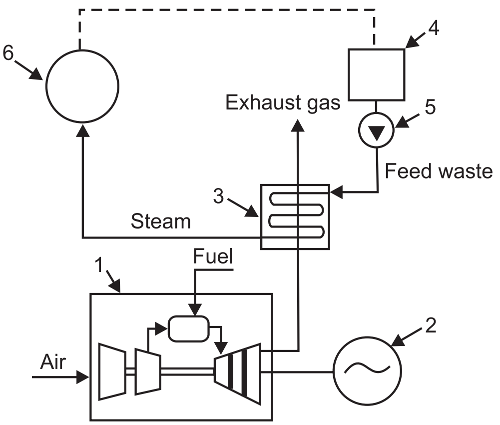

The second type of system burns fuel (any type) to produce high-pressure steam that then passes through a steam turbine to produce power with the exhaust provides low-pressure process steam. This is a steam-turbine topping system.

(b)




A third type employs heat recovery from an engine exhaust and/or jacket cooling system flowing to a heat recovery boiler, where it is converted to process steam/hot water for further use.

(c)




The fourth type is a gas-turbine topping system. A natural gas turbine drives a generator. The exhaust gas goes to a heat recovery boiler that makes process steam and process heat.

(d)

**Figure 19.6** Types of topping cycles

### 19.5.2 Bottoming cycle

In a bottoming cycle, the primary fuel produces high temperature thermal energy and the heat rejected from the process is used to generate power through a recovery boiler and a turbine generator. Bottoming cycles are suitable for manufacturing processes that require heat at high temperature in furnaces and kilns, and reject heat at significantly high temperatures. Typical areas of application include cement, steel, ceramic, gas and petrochemical industries. Bottoming cycle plants are much less common than topping cycle plants. Figure 19.7 illustrates the bottoming cycle where fuel is burnt in a furnace to produce synthetic rutile. The waste gases coming out of the furnace is utilised in a boiler to generate steam, which drives the turbine to produce electricity.

## 19.6 Factors influencing cogeneration choice

The selection and operating scheme of a cogeneration system is very much site-specific and depends on several factors, as described below.

### 19.6.1 Base electrical load matching

In this configuration, the cogeneration plant is sized to meet the minimum electricity demand of the site based on the historical demand curve. The rest of the needed power is purchased from the utility grid. The thermal energy requirement of the site could be met by the cogeneration system alone or by additional boilers. If the thermal energy generated with the base electrical load exceeds the plant's demand and if the situation permits, excess thermal energy can be exported to neighbouring customers.

### 19.6.2 Base thermal load matching

Here, the cogeneration system is sized to supply the minimum thermal energy requirement of the site. Stand-by boilers or burners are operated during periods when the demand for heat is higher. The prime mover installed operates at full load at all times. If the electricity demand of the site exceeds that which can be provided by the prime mover, then the remaining amount can be purchased from the grid. Likewise, if local laws permit, the excess electricity can be sold to the power utility.

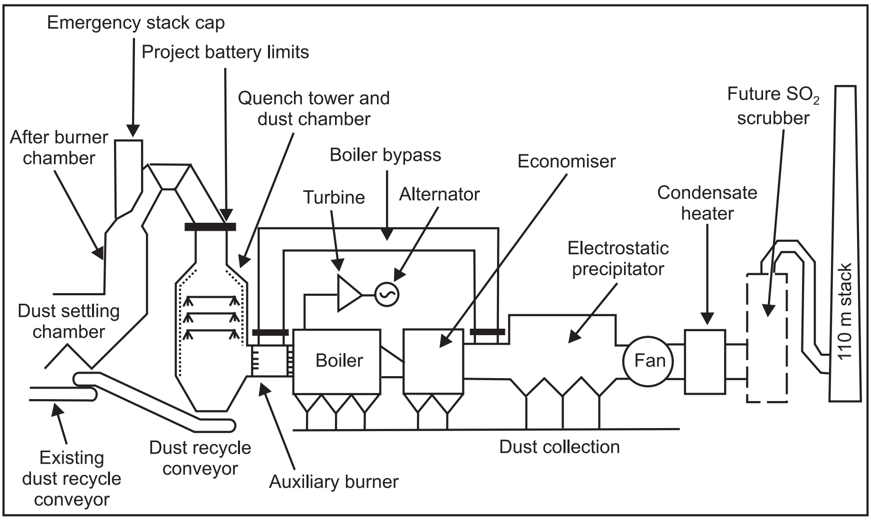



**Figure 19.7** Bottoming cycle

### 19.6.3 Electrical load matching

In this operating scheme, the facility is totally independent of the power utility grid. All the power requirements of the site, including the reserves needed during scheduled and unscheduled maintenance, are to be taken into account while sizing the system. This is also referred to as a 'stand-alone' system. If the thermal energy demand of the site is higher than that generated by the cogeneration system, auxiliary boilers are used. On the other hand, when the thermal energy demand is low, some thermal energy is wasted. If there is a possibility, excess thermal energy can be exported to neighbouring facilities.

### 19.6.4 Thermal load matching

The cogeneration system is designed to meet the thermal energy requirement of the site at any time. The prime movers are operated following the thermal demand. During the period when the electricity demand exceeds the generation capacity, the deficit can be compensated by power purchased from the grid. Similarly, if the local legislation permits, electricity produced in excess at any time may be sold to the utility.

## 19.7 Important technical parameters for cogeneration

While selecting cogeneration systems, one should consider some important technical parameters that assist in defining the type and operating scheme of different alternative cogeneration systems to be selected.

### 19.7.1 Heat-to-power ratio

Heat-to-power ratio is one of the most important technical parameters influencing the selection of the type of cogeneration system. The heat-to-power ratio of a facility should match with the characteristics of the cogeneration system to be installed. It is defined as the ratio of thermal energy to electricity required by the energy consuming facility. Though it can be expressed in different units such as Btu/kWh, kcal/kWh, lb/hr/kW, etc. here it is presented on the basis of the same energy unit (kW).

Basic heat-to-power ratios of the different cogeneration systems are shown in Table 19.1 along with some technical parameters. The steam turbine cogeneration system can offer a large range of heat-to- power ratios.

**Table 19.1** Heat-to-power ratios and other parameters of cogeneration systems.

| Cogeneration system | Heat-to-power ratio (kWth/kWe) | Power output (as per cent of fuel input) | Overall efficiency (per cent) |
|---|---|---|---|
| Back-pressure steam turbine | 4.0–14.3 | 14–28 | 84–92 |
| Extraction-condensing steam turbine | 2.0–10.0 | 22–40 | 60–80 |
| Gas turbine | 1.3–2.0 | 24–35 | 70–85 |
| Combined cycle | 1.0–1.7 | 34–40 | 69–83 |
| Reciprocating engine | 1.1–2.5 | 33–53 | 75–85 |

Cogeneration uses a single process to generate both electricity and usable heat or cooling. The proportions of heat and power needed (heat: power ratio) vary from site to site, so the type of plant must be selected carefully and appropriate operating schemes must be established to match demands as closely as possible. The plant may therefore be set up to supply part or all of the site heat and electricity loads, or an excess of either may be exported if a suitable customer is available. Table 19.2 shows typical heat:power ratios for certain energy intensive industries.

**Table 19.2** Typical heat: power ratios for certain energy intensive industries.

| Industry | Minimum | Maximum | Average |
|---|---|---|---|
| Breweries | 1.1 | 4.5 | 3.1 |
| Pharmaceuticals | 1.5 | 2.5 | 2.0 |
| Fertilizer | 0.8 | 3.0 | 2.0 |
| Food | 0.8 | 2.5 | 1.2 |
| Paper | 1.5 | 2.5 | 1.9 |

Cogeneration is likely to be most attractive under the following circumstances:

1. The demand for both steam and power is balanced, i.e. consistent with the range of steam:power output ratios that can be obtained from a suitable cogeneration plant.
2. A single plant or group of plants has sufficient demand for steam and power to permit economies of scale to be achieved.
3. Peaks and troughs in demand can be managed or, in the case of electricity, adequate backup supplies can be obtained from the utility company.

The ratio of heat to power required by a site may vary during different times of the day and seasons of the year. Importing power from the grid can make up a shortfall in electrical output from the cogeneration unit and firing standby boilers can satisfy additional heat demand. Many large cogeneration units utilise supplementary or boost firing of the exhaust gases in order to modify the heat:power ratio of the system to match site loads.

## 19.7.2 Quality of thermal energy needed

The quality of thermal energy required (temperature and pressure) also determines the type of cogeneration system. For a sugar mill needing thermal energy at about 120°C, a topping cycle cogeneration system can meet the heat demand. On the other hand, for a cement plant requiring thermal energy at about 1450°C, a bottoming cycle cogeneration system can meet both high quality thermal energy and electricity demands of the plant.

### 19.7.3 Load patterns

The heat and power demand patterns of the user affect the selection (type and size) of the cogeneration system. For instance, the load patterns of two energy consuming facilities shown in Fig. 19.8 would lead to two different sizes, possibly types also, of cogeneration systems.

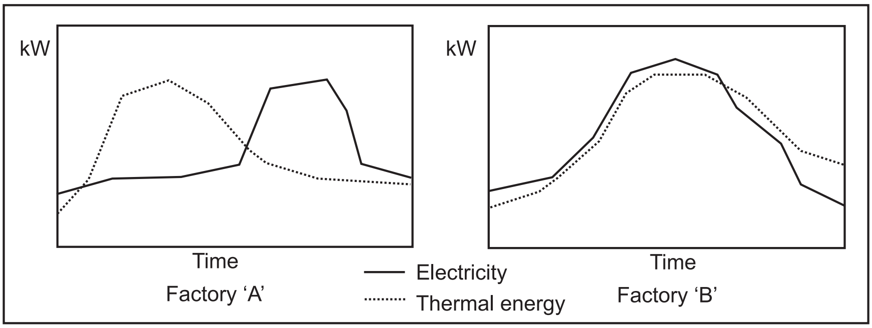



**Figure 19.8** Different heat and power demand patterns in two factories

### 19.7.4 Fuels available

Depending on the availability of fuels, some potential cogeneration systems may have to be rejected. The availability of cheap fuels or waste products that can be used as fuels at a site is one of the major factors in the technical consideration because it determines the competitiveness of the cogeneration system. A rice mill needs mechanical power for milling and heat for paddy drying. If a cogeneration system were considered, the steam turbine system would be the first priority because it can use the rice husk as the fuel, which is available as waste product from the mill.

### 19.7.5 System reliability

Some energy consuming facilities require very reliable power and/or heat; for instance, a pulp and paper industry cannot operate with a prolonged unavailability of process steam. In such instances, the cogeneration system to be installed must be modular, i.e. it should consist of more than one unit so that shut down of a specific unit cannot seriously affect the energy supply.

### 19.7.6 Grid dependent system versus independent system

A grid-dependent system has access to the grid to buy or sell electricity. The grid-independent system is also known as a ‘stand-alone’ system that meets all the energy demands of the site. It is obvious that for the same energy consuming facility, the technical configuration of the cogeneration system designed as a grid dependent system would be different from that of a stand-alone system.

### 19.7.7 Retrofit versus new installation

If the cogeneration system is installed as a retrofit, the system must be designed so that the existing energy conversion systems, such as boilers, can still be used. In such a circumstance, the options for cogeneration system would depend on whether the system is a retrofit or a new installation.

### 19.7.8 Electricity buy-back

The technical consideration of cogeneration system must take into account whether the local regulations permit electric utilities to buy electricity from the cogenerators or not. The size and type of cogeneration system could be significantly different if one were to allow the export of electricity to the grid.

### 19.7.9 Local environmental regulation

The local environmental regulations can limit the choice of fuels to be used for the proposed cogeneration systems. If the local environmental regulations are stringent, some available fuels cannot be considered because of the high treatment cost of the polluted exhaust gas and in some cases, the fuel itself.

## 19.8 Prime movers for cogeneration

### 19.8.1 Steam turbine

Steam turbines are the most commonly employed prime movers for cogeneration applications. In the steam turbine, the incoming high pressure steam is expanded to a lower pressure level, converting the thermal energy of high pressure steam to kinetic energy through nozzles and then to mechanical power through rotating blades.

*Back pressure turbine:* In this type steam enters the turbine chamber at high pressure and expands to low or medium pressure. Enthalpy difference is used for generating power/work.

Depending on the pressure (or temperature) levels at which process steam is required, backpressure steam turbines can have different configurations as shown in Fig. 19.9.

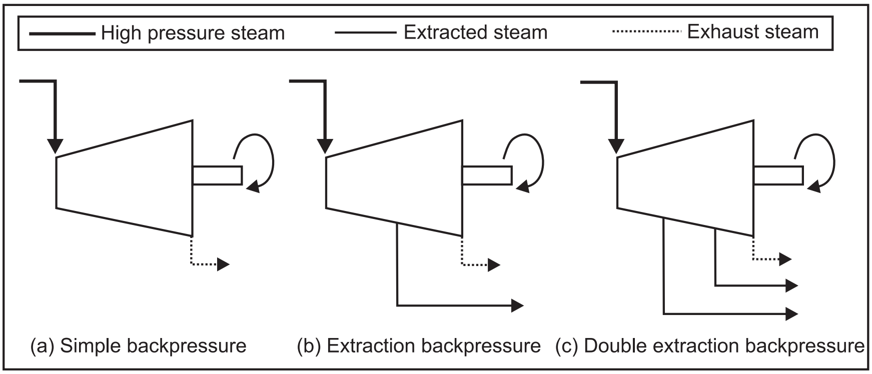



**Figure 19.9** Different configurations for back pressure steam turbines

In extraction and double extraction backpressure turbines, some amount of steam is extracted from the turbine after being expanded to a certain pressure level. The extracted steam meets the heat demands at pressure levels higher than the exhaust pressure of the steam turbine.

The efficiency of a backpressure steam turbine cogeneration system is the highest. In cases where 100 per cent backpressure exhaust steam is used, the only inefficiencies are gear drive and electric generator losses, and the inefficiency of steam generation.

Therefore, with an efficient boiler, the overall thermal efficiency of the system could reach as much as 90 per cent.

*Extraction condensing turbine:* In this type, steam entering at high/ medium pressure is extracted at an intermediate pressure in the turbine for process use while the remaining steam continues to expand and condenses in a surface condenser and work is done till it reaches the condensing pressure (vacuum).

In extraction-cum-condensing steam turbine as shown in Fig. 19.10, high pressure steam enters the turbine and passes out from the turbine chamber in stages. In a two stage extraction-cum-condensing turbine MP steam and LP steam pass out to meet the process needs. Balance quantity condenses in the surface condenser. The energy difference is used for generating power. This configuration meets the heat-power requirement of the process.

The extraction condensing turbines have higher power to heat ratio in comparison with backpressure turbines. Although condensing systems need more auxiliary equipment such as the condenser and cooling towers, better matching of electrical power and heat demand can be obtained where electricity demand is much higher than the steam demand and the load patterns are highly fluctuating.

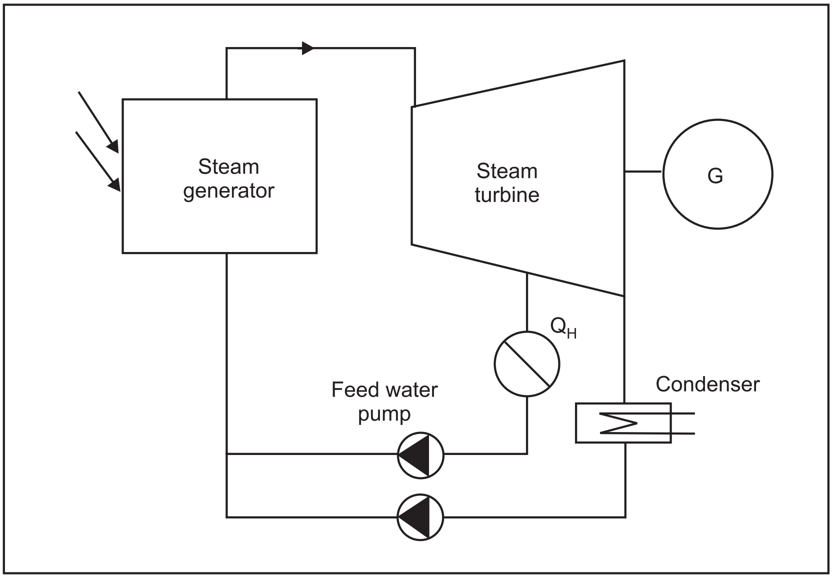



**Figure 19.10** Extraction condensing turbine

The overall thermal efficiency of an extraction condensing turbine cogeneration system is lower than that of back pressure turbine system, basically because the exhaust heat cannot be utilised (it is normally lost in the cooling water circuit). However, extraction condensing cogeneration systems have higher electricity generation efficiencies.

## 19.8.2 Gas turbine

The fuel is burnt in a pressurised combustion chamber using combustion air supplied by a compressor that is integral with the gas turbine. In conventional gas turbine, gases enter the turbine at a temperature range of 900° to 1000°C and leave at 400° to 500°C.

The very hot pressurised gases are used to turn a series of turbine blades, and the shaft on which they are mounted, to produce mechanical energy. Residual energy in the form of a high flow of hot exhaust gases can be used to meet, wholly or partly, the thermal (steam) demand of the site. Waste gases are exhausted from the turbine at 450°C to 550°C, making the gas turbine particularly suitable for high-grade heat supply.

The available mechanical energy can be applied in the following ways:

1. To produce electricity with a generator (most applications).
2. To drive pumps, compressors, blowers, etc.

A gas turbine operates under exacting conditions of high speed and high temperature. The hot gases supplied to it must therefore be clean (i.e. free of particulates which would erode the blades) and must not contain more than minimal amounts of contaminants, which would cause corrosion under operating conditions. High-premium fuels are therefore most often used, particularly natural gas. Distillate oils such as gas oil are also suitable, and sets capable of using both are often installed to take advantage of cheaper interruptible gas tariffs. LPGs and Naphtha are also suitable, LPG being a possible fuel in either gaseous or liquid form.

### *Gas turbine efficiency*

Turbine efficiency is the ratio of actual work output of the turbine to the net input energy supplied in the form of fuel. For stand-alone gas turbines, without any heat recovery system the efficiency will be as low as 35 to 40 per cent. This is attributed to the blade efficiency of the rotor, leakage through clearance spaces, friction, irreversible turbulence, etc.

Since exhaust gas from the gas turbine is high, it is possible to recover energy from the hot gas by a heat recovery steam generator and use the steam for process.

### *Net turbine efficiency*

Above efficiency figures did not include the energy consumed by air compressors, fuel pump and other auxiliaries. Air compressor alone consumes about 50 to 60 per cent of energy generated by the turbine. Hence net turbine efficiency, which is the actual energy output available will be less than what has been calculated. In most gas turbine plants, air compressor is an integral part of turbine plant.

## 19.8.3 Reciprocating engine systems

This system provides process heat or steam from engine exhaust. The engine jacket cooling water heat exchanger and tube oil cooler may also be used to provide hot water or hot air. There are, however, limited applications for this. As these engines can use only fuels like HSD, distillate, residual oils, natural gas, LPG, etc. and as they are not economically better than steam/gas turbine, their use is not widespread for cogeneration. One more reason for this is the engine maintenance requirement (Fig. 19.11).

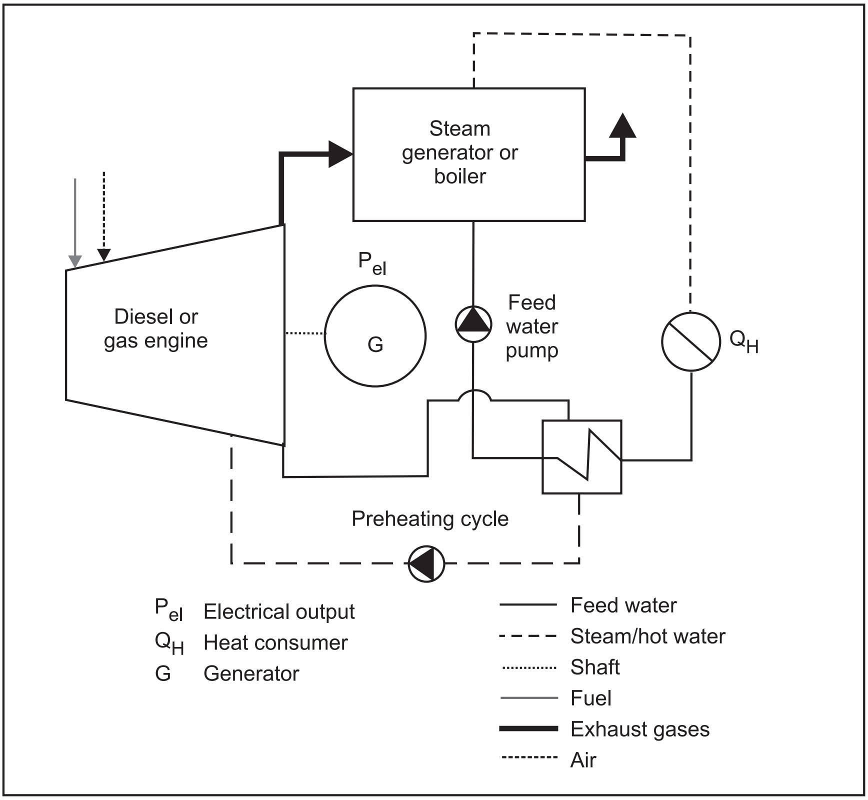



**Figure 19.11** Reciprocating engine systems

## 19.9 Typical cogeneration performance parameters

Table 19.3 gives typical cogeneration performance parameters for different cogeneration packages giving heat rate, overall efficiencies, etc.

**Table 19.3** Typical cogeneration performance parameters.

| Prime mover in cogeneration package | Nominal range (electrical) | Electrical generation heat rate (kCal/kWH) | Efficiencies, % | | |
|---|---|---|---|---|---|
| | | | Electrical conversion | Thermal recovery | Overall ogeneration |
| Smaller reciprocating engines | 10–500 kW | 2650–6300 | 20–32 | 50 | 74-82 |
| Larger reciprocating engines | 500–3000 kW | 2400–3275 | 26–36 | 50 | 76–86 |
| Diesel engines | 10–3000 kW | 2770–3775 | 23–38 | 50 | 73–88 |
| Smaller gas turbines | 800–10,000 kW | 2770–3525 | 24–31 | 50 | 74–81 |
| Larger gas turbines | 10–20 MW | 2770–3275 | 26–31 | 50 | 78–81 |
| Steam turbines | 10–100 MW | 2520–5040 | 17–34 | – | – |

## 19.10 Relative merits of cogeneration systems

Table 19.4 gives the advantages and disadvantages of various cogeneration systems.

**Table 19.4** Advantages and disadvantages of various cogeneration systems.

| Variant | Advantages | Disadvantages |
|---|---|---|
| Back pressure | High fuel efficiency rating | Little flexibility in design and operation |
| Steam turbine and fuel firing in boiler | Simple plant<br>Well-suited to low quality fuels | More capital investment<br>Low fuel efficiency rating<br>High cooling water demand<br>More impact on environment<br>High civil const. cost due to complicated foundations |
| Gas turbine with waste heat recovery boiler | Good fuel efficiency<br>Simple plant<br>Low civil const. cost<br>Less delivery period<br>Less impact on environment<br>High flexibility in operation | Moderate part-load efficiency<br>Limited suitability for low quality fuels |

*Cont...*

*Cont...*

| Variant | Advantages | Disadvantages |
|---|---|---|
| Combined gas and steam turbine with waste heat recovery boiler | Optimum fuel efficiency rating<br>Low relative capital cost<br>Less gestation period<br>Quick start up and stoppage<br>Less impact on environment<br>High flexibility in operation | Average to moderate part-load efficiency<br>Limited suitability for low quality fuels |
| Diesel engine and waste heat recovery<br>Boiler and cooling water heat exchanger | Low civil const. Cost due to block foundations and least number of auxiliaries<br>High power efficiency<br>Better suitability as stand by power source | Low overall efficiency<br>Limited suitability for low quality fuels<br>Availability of low temperature steam<br>Highly maintenance prone |

# 20
# Photosynthesis

## 20.1 Introduction

Photosynthesis is a chemical process that converts carbon dioxide into organic compounds, especially sugars, using the energy from sunlight. Photosynthesis occurs in plants, algae and many species of bacteria, but not in archaea. Photosynthetic organisms are called photoautotrophs, since they can create their own food. In plants, algae, and cyanobacteria, photosynthesis uses carbon dioxide and water, releasing oxygen as a waste product. Photosynthesis is vital for all aerobic life on earth.

An example of naturally occurring biological oxidation–reduction reactions is the process of photosynthesis. It is a very complex process carried out by green plants, blue-green algae, and certain bacteria. These organisms are able to harness the energy contained in sunlight, and via a series of oxidation–reduction reactions, produce oxygen and sugar, as well as other compounds which may be utilised for energy as well as the synthesis of other compounds. The overall equation for the photosynthetic process may be expressed as:

$$6CO_2 + 6H_2O \rightarrow \underset{\text{(Glucose)}}{C_6H_{12}O_6} + 6O_2$$

The equation is the net result of two processes. One process involves the splitting of water. This process is really an oxidative process that requires light, and is often referred to as the 'light reaction'. This reaction may be written as:

$$12H_2O \xrightarrow{\text{Light or radiant energy}} 6CO_2 + 24H^+ + 24e^-$$

The oxidation of water is accompanied by a reduction reaction resulting in the formation of a compound, called nicotinamide adenine dinucleotide phosphate (NADPH). This reaction is illustrated below:

$$\underset{\text{(Oxidised form)}}{NADP^+} + H_2O \rightarrow \underset{\text{(Reduced form)}}{NADPH} + H^+ + \underset{\text{(Oxygen)}}{O}$$

This reaction is linked or coupled to yet another reaction resulting in the formation of a highly energetic compound called adenosine triphosphate (ATP). As this reaction involves the addition of a phosphate group (labelled as Pi) to a compound called adenosine diphosphate (ADP) during the light reaction, it is called photophosphorylation.

$$ADP + Pi \rightarrow ATP$$

Think of the light reaction, as a process by which organisms 'capture and store' radiant energy as they produce oxygen gas. This energy is stored in the form of chemical bonds of compounds such as NADPH and ATP. The energy contained in both NADPH and ATP is then used to reduce carbon dioxide to glucose, a type of sugar ($C_6H_{12}O_6$). This reaction, shown below, does not require light, and it is often referred to as the 'dark reaction'.

$$6CO_2 + 24H^+ + 24e^- \rightarrow C_6H_{12}O_6 + 6H_2O$$

The chemical bonds present in glucose also contain a considerable amount of potential energy. This stored energy is released whenever glucose is catabolised (broken down) to drive cellular processes. The carbon skeleton in glucose also serves as a source of carbon for the synthesis of other important biochemical compounds such as, lipids, amino acids and nucleic acids.

In simplest terms, the process of photosynthessis can be viewed as one-half of the carbon cycle. In this half, energy from the sun is captured and transformed into nutrients which can be utilised by higher organisms in the food chain. The release of this energy during the metabolic re-conversion of glucose to water and carbon dioxide represents the second half of the carbon cycle and it may be referred to as catabolism or 'oxidative processes'.

## 20.2 Photosynthesis and biomass

### 20.2.1 Photosynthetic efficiency

Approximately 114 kilocalories of free energy are stored in plant biomass for every mole of $CO_2$ fixed during photosynthesis. Solar radiation striking the earth on an annual basis is equivalent to 1,78,000 terawatts, i.e. 15,000 times that of current global energy consumption. Although photosynthetic energy capture is estimated to be ten times that of global annual energy consumption, only a small part of this solar radiation is used for photosynthesis. Approximately two-third of the net global photosynthetic productivity worldwide is of terrestrial origin, while the remainder is produced mainly by phytoplankton (microalgae) in the oceans which cover approximately 70 per cent of the total surface area of the earth. Since biomass originates from plant and algal photosynthesis, both terrestrial plants and microalgae are appropriate targets for scientific studies relevant to biomass energy production.

Any analysis of biomass energy production must consider the potential efficiency of the processes involved. Although photosynthesis is fundamental to the conversion of solar radiation into stored biomass energy, its theoretically achievable efficiency is limited both by the limited wavelength range applicable to photosynthesis, and the quantum requirements of the photosynthetic process. Only light within the wavelength range of 400 to 700 nm (photosynthetically active radiation, PAR) can be utilised by plants, effectively allowing only 45 per cent of total solar energy to be utilised for photosynthesis. Furthermore, fixation of one $CO_2$ molecule during photosynthesis, necessitates a quantum requirement of ten (or more), which results in a maximum utilisation of only 25 per cent of the PAR absorbed by the photosynthetic system. On the basis of these limitations, the theoretical maximum efficiency of solar energy conversion is approximately 11 per cent. In practice, however, the magnitude of photosynthetic efficiency observed in the field, is further decreased by factors such as poor absorption of sunlight due to its reflection, respiration requirements of photosynthesis and the need for optimal solar radiation levels; the net result being an overall photosynthetic efficiency of between 3 and 6 per cent of total solar radiation.

Photosynthetic microalgae are potential candidates for utilising excessive amounts of $CO_2$, since when cultivated these organisms are capable of fixing $CO_2$ to produce energy and chemical compounds upon exposure to sunlight. The derivation of energy from algal biomass is an attractive concept in that unlike fossil fuels, algal biomass is rather uniformly distributed over much of the earth's surface, and its utilisation would make no net contribution to increasing atmospheric $CO_2$ levels. Although algal biomass is regarded as a low-grade energy source owing to its high moisture content, through biological processes, it may be converted to modern gaseous and liquid fuels such as hydrogen, methane, ethanol, and oils.

Hydrogen is regarded as a potential energy source of the future, since it is easily converted to electricity and burns cleanly. Hydrogen is currently produced by fossil fuel-based processes which emit large amounts of $CO_2$, and relatively smaller amounts of other air pollutants such as sulphur dioxide and nitrogen oxides. Biological $H_2$ production has thus recently received renewed attention owing to urban air pollution and global warming concerns. Biological hydrogen production methodologies incorporating artificial reconstitution systems with chloroplast, ferredoxin, and hydrogenase; a heterocystous cyanobacterial system with oxygen scavengers; and an algal system in a day-and-night cycle, have been studied in Japan. From an engineering point of view, however, bacterial fermentation mechanisms for hydrogen production under either dark or light conditions is currently of importance in terms of environmental issues and the utilisation of organic wastes such as waste effluent of the food and fermentation industries, pretreated sewage sludge, and market garbage.

The use of microalgae as sources of liquid fuels is an attractive proposition from the point of view that microalgae are photosynthetic renewable resources, are of a high lipid content, have faster growth rates than plant cells, and are capable of growth in saline waters which are unsuitable for agriculture. While the lipid content of microalgae, on a dry cellular weight basis varies between 20 and 40 per cent, lipid contents as high as 85 per cent have been reported for certain microalgal strains. Botryococcus braunii is a unique microalgal strain, having a long-chain hydrocarbon content of between 30 and 40 per cent (dry weight basis), which is directly extractable to yield crude oil substitutes. Both physical and chemical processes are applicable in the production of liquid fuels from algal strains of high lipid content. These processes include direct lipid extraction in the production of diesel-oil substitutes, transesterification in the formation of ester fuels, and hydrogenation in the production of hydrocarbons. Oily substances are also produced via liquefaction of microalgal biomass through thermochemical reactions under conditions of high pressure and temperature.

### 20.2.2 General problems

Among the biomass conversion processes discussed thus far, methane and ethanol production from various wastes is economically feasible within the restraints of scale and location. Although biological processes for the production of gaseous and liquid fuels have been well demonstrated with cultured microalgal biomass, these processes must still be integrated into a system capable of meeting basic requirements for overall efficiency of converting solar energy into biofuels. Furthermore, a model system must at least in principle, be capable of easy scale-up and not be limited by either engineering or economic factors. Under the current petroleum economy, prospects for the use of $H_2$ or oils produced by biological processes seem remote. However, future requirements for a ‘clean environment’ necessitate fundamental research into microbial and algal physiology and genetics, together with basic engineering research on converters and total systems.

## 20.3 Photosynthetic capture of solar energy

Approximately $5.7 \times 10^{24}$ J of solar energy is irradiated to the earth’s surface on an annual basis. Plants and photosynthetic organisms utilise this solar energy in fixing large amounts of $CO_2$ ($2 \times 10^{11}$ t = $3 \times 10^{21}$ J/year), while amounts consumed by human beings are relatively small, ($3 \times 10^{20}$ J/year), representing only 10 per cent of the energy converted during photosynthesis. Although large amounts of solar energy are irradiated to the earth’s surface, the effective energy concentration (energy/unit area) of solar energy at any one point on the earth's surface is small—only about 1 $kW/m^2$ at most, even at noon. Such low effective energy concentrations, limit the use of solar energy as a primary energy source, and elevate the costs associated with its accumulation and transmission.

Technologies for the utilisation of low-density energy sources must be developed in order to facilitate the use of solar energy. Solar energy conversions through the use of photosynthetic micro-organisms do not incorporate the use of complex systems or large quantities of factory manufactured products, and indeed have relatively minimal investment and resource requirements. Additionally, these technologies are largely dependent on the use of renewable resources, thereby generating minimal amounts of waste. Recent advances in biotechnology have made possible studies on the utilisation of biological processes such as photosynthesis for energy production.

### 20.3.1 Biotechnology and energy technology

The use of natural energy involves the control of entropy. Prior to the industrial revolution, wood served as a major energy source. However, the industrial revolution gave rise to the widespread use of both coal and petroleum as energy sources. Since coal and petroleum were often produced at sites far from their consumption points, recuperation of their production costs involved mass production, thus precipitating the formation of an integrated industrial society. This integrated system soon reached its limits, making it necessary to consider discrete social systems that utilise delocalised abundant energy sources.

Integration is necessary in any system where energy, goods, and information are dispersed. Integration of systems involves the use of entropy-reducing processes. Application of mechanical methods to the integration of systems incorporates large amounts of energy expenditure. Existing problems cannot therefore be resolved without modification of existing social systems. Consequently, energy production technology must be reformed. Micro-organisms have the ability to reduce entropy through energy utilisation, and can potentially simplify the conversion and accumulation of solar energy and energy utilisation over large areas.

Following the industrial revolution, energy-releasing techniques were developed. The development of techniques which control entropy are essential for human survival. To this end, there is a need for the development of industrial technology which makes use of biological principles in a sophisticated manner.

## 20.4 Photosynthesis mechanisms

Biological energy conversions can be categorised into two groups: (i) photosynthesis (the process whereby solar energy is fixed to yield energy useful to organisms and industry), and (ii) biomass conversion (the product of photosynthesis) into energy. Photosynthesis occurs in plants, algae and photosynthetic bacteria, while biomass conversion reactions often occur in non-photosynthetic micro-organisms. This section focuses on photosynthetic processes.

### 20.4.1 Plant photosynthesis

Photosynthesis is often regarded as a $CO_2$ anabolic reaction, whereby glucose is formed from $CO_2$ and water. $CO_2$ anabolism is an energy-consuming reaction in that it utilises chemical energy produced by photosynthesis. In its narrowest sense, photosynthesis can be regarded as a process whereby energy is supplied for $CO_2$ anabolism. In a broader sense, photosynthesis, including $CO_2$ anabolism, can be divided into several steps: (i) photoelectric charge isolation using photon energy (conversion to electrical energy), (ii) fixation of electrical energy in the form of chemical energy (ATP synthesis), and (iii) chemical reactions involving ATP (fixation of $CO_2$, and hydrogen production).

The supply of energy for $CO_2$ anabolism is common to all photosynthetic organisms which exhibit photosynthesis. Energy conversion, ATP synthesis and the production of both $CO_2$ and hydrogen on the other hand, are not unique to photosynthetic organisms, but occur in all types of micro-organisms, and are in fact similar to the respiratory processes which occur in mitochondria of higher organisms.

Two types of photosynthesis are distinguishable on the basis of source of the electrons used as energy carriers. In plants such as green algae, and cyanobacteria (blue-green algae), water is the electron source, while in photosynthetic bacteria, organic or sulphur compounds provide electron sources.

Photosynthetic mechanisms which occur within plant photosynthetic membranes are schematically presented in Fig. 20.1. Two photosystem II water molecules are initially decomposed by four incident photons, to yield one oxygen molecule and four excited electrons. Excited electron energy is subsequently utilised in ATP synthesis. Unlike in the case of ordinary chemical reactions, ATP synthesis cannot be stoichiometrically analysed.

The ratio of excited photons to ATP produced is still a somewhat debatable issue. Although it has generally been thought that two photons give rise to the formation of two ATP molecules, some researchers claim that three photons are involved. Furthermore, other researchers have suggested a loose coupling between proton transport and ATP synthesis:

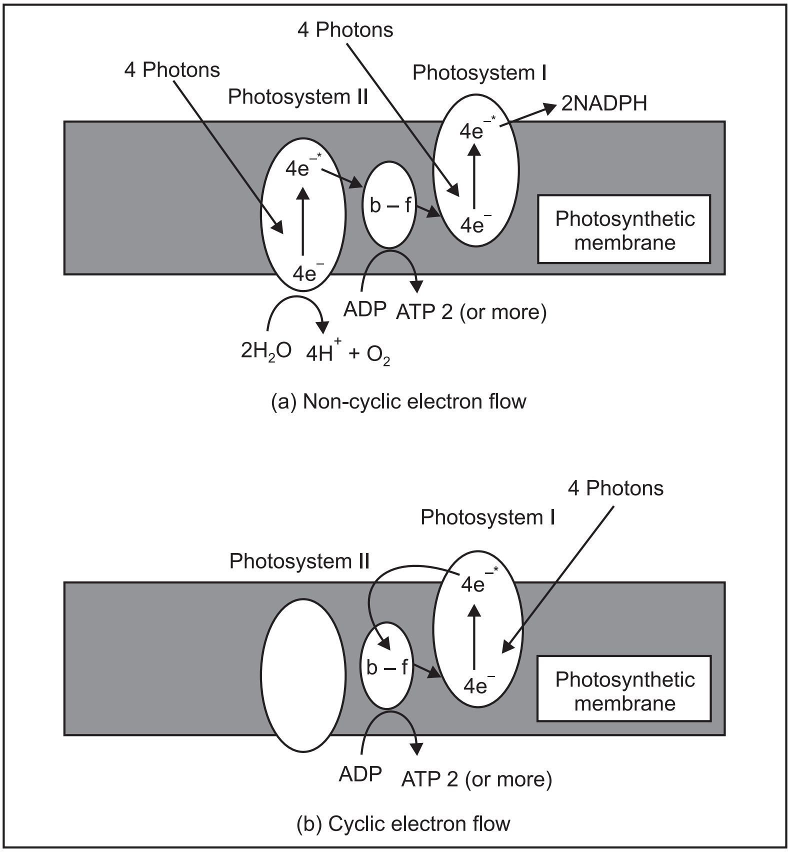



**Figure 20.1** Schematic representation of mechanisms involved in plant photosynthesis

$$4 \text{ Photons} + 2H_2O + 2 \text{ (or more) } ADP = 2 \text{ (or more) } ATP + 4H+ + 4e^- + O_2 \quad ...(20.1)$$

Subsequent to their energy release in ATP production, photosystem II electrons are transported to photosystem I, where they are again excited to a higher energy level, allowing them to be utilised for NADP reduction. NADP serves both as an electron carrier and an oxidising and reducing agent in vivo. Two photons are utilised per molecule of NADP reduced:

$$4 \text{ Photons} + 4e^- + 2NADP + 4H+ = 2NADPH \quad ...(20.2)$$

Photosystem I may also be involved in ATP synthesis. In cases where it is involved, excited photosystem I electrons are recycled:

$$4 \text{ Photons} + 2 \text{ (or more) ADP} = 2 \text{ (or more) ATP} \quad \text{... (20.3)}$$

Fixation of one molecule of $CO_2$, involves the following equation:

$$CO_2 + 3ATP + 2NADPH = CH_2O + 3ADP + 2NADP \quad \text{... (20.4)}$$

If two ATP molecules are obtained through Photosystem II excitation (Eq. 20.1), the net reaction following Eqs. 20.1 to 20.4 is:

$$CO_2 + 10 \text{ Photons} + H_2O = CH_2O + 1/2O_2 \quad \text{... (20.5)}$$

Experimental data indicates that between 8 and 12 photons are required for fixation of one molecule of $CO_2$. Since the energy equivalent of one photon (700 nm) is approximately 170 kJ/E, and the change in free energy during the fixation of $CO_2$ is approximately 450 U/mol, the energy efficiency of this process for monochromatic light of a wavelength of 700 nm is estimated to be approximately 21–33 per cent. However, owing to the quantum nature of photosynthetic reactions, energy efficiency decreases if light of shorter wavelengths (i.e. higher quantum energy) is used. Additionally, energy losses, energy requirements for plant growth, and the distribution of solar energy wavelengths need to be considered.

Plant photosynthesis takes place only in the presence of visible light (400–700 nm). However, solar light contains both visible and infrared components. Since visible light accounts for about 45 per cent of all solar energy, the maximum achievable energy efficiency for $CO_2$ fixation using solar radiation is approximately 13 per cent.

## 20.4.2 Bacterial photosynthesis

Bacterial photosynthesis is thought to be a relatively old form of photosynthesis. It incorporates the use of either organic or sulphur compounds as electron donors in photosystem I (Fig. 20.2). Unlike in the case of plant photosynthesis, cyclic photophosphorylation takes place in bacterial photosynthesis, i.e. electrons are repeatedly excited in a cyclic manner, with ATP being generated in each cycle. Photosynthetic bacteria are also capable of reducing electron carriers such as NAD, via a linear reaction similar to the electron transmission which occurs during plant photosynthesis (Fig. 20.2).

$CO_2$-fixing reactions do not produce energy during bacterial photosynthesis (i.e. equimolar amounts of organic compounds are produced through decomposition of organic compounds), except when sulphur compounds serve as electron carriers.

$$2 \text{ Photons} + 1 \text{ (or more) ADP} = 1 \text{ (or more) ATP} \quad \text{... (20.6)}$$

Electrons are donated as follows:

$$CH_2O + H_2O = 4e^- + 4H^+ + CO_2 \quad \text{... (20.7)}$$

The structure of the photosynthetic reaction centre (RC), involved in the early steps of photosynthesis, has been elucidated for certain photosynthetic bacteria (Fig. 20.3). Such chlorophyll-containing bacteria, which include Rhodopseudomonas viridis and Rhodobacter sphaeroides, show similarities with respect to the arrangement of chlorophyll, and the three-dimensional structures of major portions of the proteins possessing that pigment. Such structural similarities between photosynthetic bacteria, seem to suggest the acquisition of an optimal structure by these bacteria, over a long evolutionary period.

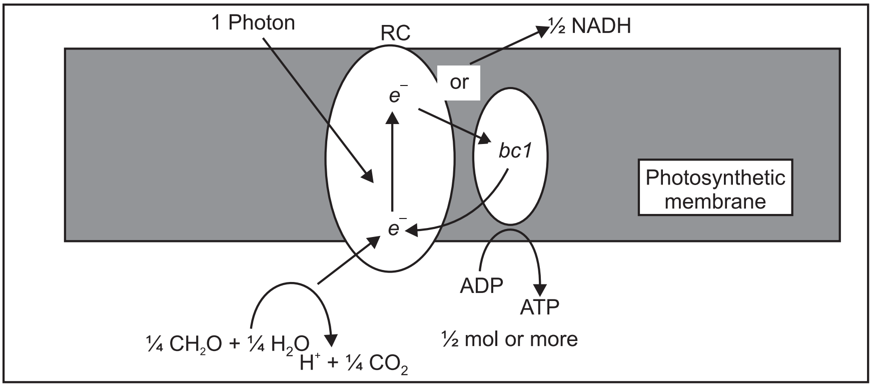



**Figure 20.2** Schematic representation of mechanisms involved in bacterial photosynthesis

Pigments such as bacteriochlorophyll are also present within the RC. Photoelectric charge isolation takes place within dimers of these bacteriochlorophyll pigments, resulting in the release of high-energy electrons, via the action of bacteriochlorophyll monomers such as bacteriopheophytin, quinone A, and quinone B. These high-energy electrons are subsequently conjugated with proton transportation in the cytochrome b/c1 complex. A noteworthy feature of the RC function is that photon involvement in photoelectric charge isolation, resembles that which occurs in photo-semiconductors. These RC centres can thus be regarded as molecular elements produced by nature. The fact that photoelectric charge isolation is observed in protein molecules will greatly influence future research relevant to molecular elements and solar batteries.

## 20.5 Hydrogen production through solar energy conversions

Although large amounts of solar energy are irradiated to the earth's surface, the actual concentration (energy/unit area) of solar energy at the earth's surface is relatively low. The accumulation of solar energy for practical use, therefore necessitates collection of solar energy over large areas. This could potentially be a costly venture, particularly with respect to the use of solar batteries for solar energy concentration. Photosynthetic bacteria however have the potential to eliminate requirements for such large batteries for solar collection. Hydrogen appears to be the most useful form of solar-converted energy, in that it can be easily substituted for petroleum-based fuels. The use of hydrogen is also advantageous in that when burnt it yields only water, and hence does not contribute to environmental pollution.

### 20.5.1 Cyanobacterial hydrogen production (plant-type photosynthesis)

Cyanobacteria (blue-green algae) and photosynthetic bacteria are representative photosynthetic hydrogen producers. *In vivo* hydrogen production by these micro-organisms is catalysed by either nitrogenase or hydrogenase enzymes. Nitrogenases require ATP for catalytic action:

$$2H^+ + 2e^{-*} (Fd) + 4ATP = H_2 + 4ADP \quad ... (20.8)$$

Hydrogenases which catalyse hydrogen production in organisms such as Clostridium, on the other hand, do not require ATP for their activity. However, since hydrogenase activity involves some hydrogen uptake, the efficiency of hydrogen production through hydrogenase activity is low. Relatively little hydrogen is produced by these organisms in the absence of strong electron donors such as ferredoxin (Fd):

$$2H^+ + e^{-*} = H_2 \quad ... (20.9)$$

(e–*: High-energy electrons in NADH, Fdred, etc.).

Where hydrogenase enzymes are used for hydrogen production and the reducing potential, yielded by photosynthetic reactions is completely used for reducing hydrogen ions, two photons can theoretically produce one hydrogen molecule:

$$2 \text{ Photons} + H_2O + 1 \text{ (or more) } ADP = 1 \text{ (or more) } ATP + 2H^+ + 2e^- + 1/2O_2 \quad ... (20.10)$$

$$2 \text{ Photons} + 2e^- = 2e^{-*} \quad ... (20.11)$$

$$2H^+ + 2e^{-*} = H_2 \text{ (by hydrogenase)} \quad ... (20.12)$$

Hydrogenase-mediated reactions in cyanobacteria are not usually biased in favour of hydrogen production. Instead, such reactions are likely to cause hydrogen uptake and are consequently impractical. It is highly likely that the high-energy electrons, yielded as a result of Clostridium or by the use of these organic substances as electron donors. The efficiency of the latter reaction can be determined by multiplying the efficiency of $CO_2$; anabolism by the efficiency of hydrogen production in photosynthetic bacteria.

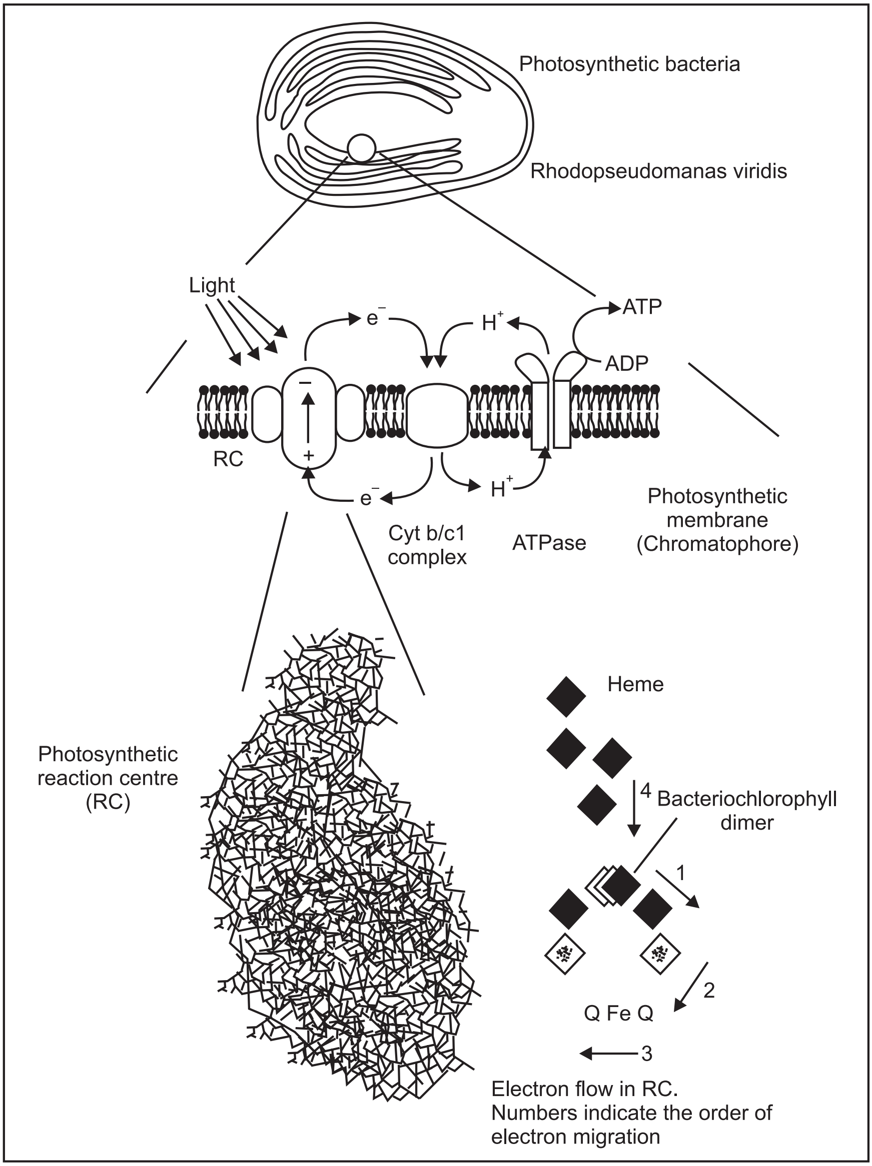



**Figure 20.3** Initial steps of photosynthesis in bacterial photosynthetic membranes

Although there are few reports of precisely determined hydrogen production efficiencies of cyanobacteria, Miyamoto determined that outdoor solar incubation for a period exceeding one month in California, resulted in an average energy conversion efficiency (energy yielded by combustion of produced hydrogen/incidence solar energy) of 0.2 per cent.

### 20.5.2 Bacterial hydrogen production (bacterial-type photosynthesis)

Bacterial mechanisms for photosynthetic hydrogen production are summarised in Fig. 20.4. Upon exposure of ammonia-free media containing photosynthetic bacteria to light, nitrogenase activity is induced, resulting in hydrogen production. Organic substances such as lactic acid serve as electron donors in photosynthetic bacteria. Anaerobes such as Clostridium also produce hydrogen, but are incapable of completely utilising energy or decomposing organic substances.

Photosynthetic bacteria are capable of completely decomposing organic substances. Studies on hydrogen production through the exposure of organic wastes (waste fluids from food factories, pulp factories, etc.) to photosynthetic bacteria and light, have been conducted in a number of countries. Research into hydrogen production using a combination of photosynthetic bacteria and anaerobes has also been conducted.

A key factor in determining the commercial applicability of hydrogen production processes, is the rate at which hydrogen is produced. Bacteria have been widely investigated for their rates of hydrogen production. To date, R. sphaeroides has been identified as the bacterium having the highest hydrogen-producing rate (260 ml/mg/hr), with a photoenergy conversion efficiency (energy yielded by combustion of produced hydrogen/incident solar energy) of 7 per cent, determined using a solar simulator. Further strain development will potentially elevate the energy conversion efficiency of photosynthetic bacteria to levels comparable to those of solar batteries.

Organic substances are utilised as electron donors by photosynthetic bacteria. The energy required for extracting electrons from these molecules is much lower than that required for the hydrolysis of water. Photo-energy is more often used for nitrogenase activation, i.e. ATP reproduction (Eq. 20.10), than for the decomposition of organic substances. The number of photons required for ATP reproduction by photosynthetic bacteria has not been theoretically elucidated, though an experimental number of 1.5 has been determined. A value of 1 has also been suggested.

In addition to ATP, nitrogenase-mediated reactions, require Fd as an electron carrier. Reaction mechanisms involved have not however been completely elucidated. The reducing potential, created in the RC of purple, non-sulphur photosynthetic bacteria such as R. sphaeroides and R. capsulatus is approximately 100 mV at most. Such bacteria would be incapable of directly reducing Fd, which has an oxidising and reducing potential of approximately 400 mV. ATP may however be capable of reducing Fd. Assuming that one ATP molecule is used for reducing one Fd molecule, at least six ATP molecules are needed for the production of one hydrogen molecule, resulting in a net requirement for nine photons. Since an 850 nm photon has an energy content of 141 kJ energy, the photon energy required for the production of hydrogen is 1269 kJ/mol $H_2$ if monochromatic light of 850 nm is used. Energy is also required for the decomposition of organic substances. This energy is however, much lower (8.5 kJ/mol $H_2$ in the case of lactic acid) than the energy required for nitrogenase-mediated reactions.

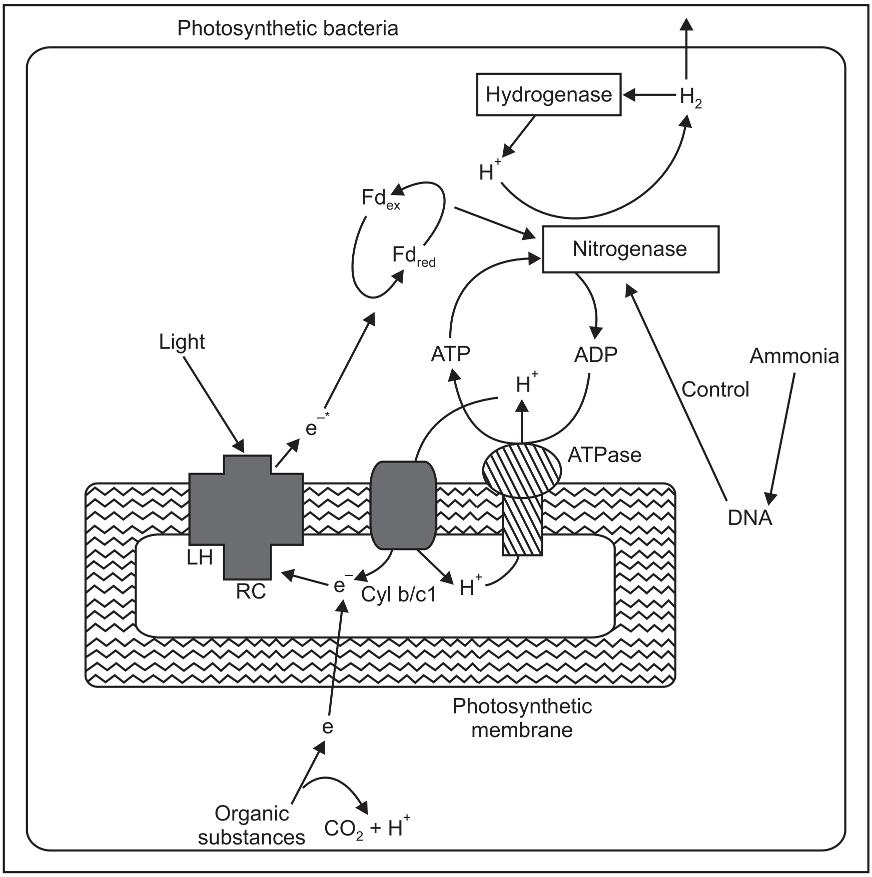



**Figure 20.4** Mechanism for hydrogen production by photosynthetic bacteria

It is unlikely that improvements can be made in the photo-energy conversion efficiencies of nitrogenases. On the other hand, hydrogenases catalyse hydrogen-producing reactions without ATP requirements (Eq. 20.9). Hydrogenase-catalysed reactions are reversible, and are either biased in favour of hydrogen production or hydrogen uptake. Hydrogenases in Clostridium and other bacteria work primarily to produce hydrogen, while hydrogenases in photosynthetic bacteria work toward hydrogen uptake. Hydrogen-producing efficiency is known to be higher in hydrogenase-deplete strains of photosynthetic bacteria.

# 21
# Ethanol

## 21.1 Introduction

Ethanol fuel is ethanol (ethyl alcohol), the same type of alcohol found in alcoholic beverages. It is most often used as a motor fuel, mainly as a biofuel additive for gasoline. Most cars on the road today in the United States can run on blends of up to 10 per cent ethanol, and the use of 10 per cent ethanol gasoline is mandated in some US states and cities.

Bioethanol is a form of renewable energy that can be produced from agricultural feedstocks. It can be made from very common crops such as sugar cane, potato, manioc and corn. There has been considerable debate about how useful bioethanol will be in replacing gasoline. Concerns about its production and use relate to increased food prices due to the large amount of arable land required for crops, as well as the energy and pollution balance of the whole cycle of ethanol production, especially from corn. Recent developments with cellulosic ethanol production and commercialisation may allay some of these concerns.

The need for automotive fuel is going to increase and, dependence of internal combustion engine as a source for transport will continue with other technological developments not posing any significant challenge to it. Among the automobiles, there are two groups of their engines, based on:

1. Constant volume cycle which in practice is our gas engines and alternatively called spark ignition engine. The fuel for this kind of engine is gasoline cut of the crude oil.
2. Constant pressure cycle which in practice is diesel engine and alternatively called compression ignition engine. The fuel for this kind of engine is diesel a major fraction of crude oil distillation.

While the latter is used for all our heavy vehicles in railway transport, in tractors, etc. the former is used for all light vehicles like cars, three wheelers and two wheelers. Overall efficiency of a gasoline engine is lower than that of a diesel engine; still it offers certain advantages due to its operation based on gasoline, a light fuel. The advantages are in the form of quick start, fast acceleration, no large emission of particulate matter (PM), no frequent major engine overhauling requirement, etc. One of the major concerns of the diesel engine is the emission of 100–200 times smaller sized PM than that in the gasoline engine exhaust. Gasoline gives the advantage of making possible two stroke engines for motor bikes, scooters, etc. without the need of cumbersome valve mechanism. The demand for light vehicles continues to grow faster than for heavy vehicles.

If the diesel and petrol prices are near to each other as is the case in other countries, the tendency of having diesel engines in cars would not be there. The recent price trends show that the gap between the prices of petrol and diesel would close. The demand for auto cycles is growing very fast. With increase in trade and urbanisation, a larger segment of population is finding it essential to use two wheelers. The per capita income is growing, and there is a corresponding increase in the use of cars also.

The fuel for such engines (spark ignition) is petrol derived by distilling crude oil taking out from the petroleum reserves. It is composed of hydrocarbons which give it a high calorific value of above 10,000 kcal/kg. Gasoline has all the desirable properties for storage, ignition, combustion and handling.

However, as narrated earlier, gasoline has two drawbacks which every petroleum derived fuel has namely that it is derived from a depleting resources and that its engines' emission increases the level of $NO_x$, $CO_2$, particulate matter and hydrocarbons in the atmosphere. For the emission of greenhouse gases (GHGs) as $NO_x$ and $CO_2$, it is a major contributor to climate change, the greatest concern of the present day.

## 21.2 Problems with gasoline

Besides the problem associated with the finiteness of petroleum reserves there is the problem of pollution caused by the engine emissions. Emission of the acid gases cause respiratory problem whereas $NO_x$ and $CO_2$ are linked to the climate change problem. $CO_2$ is the major contributor in the GHGs but since all fossil fuels invariably contain carbon there is no way out except increasing the efficiency so that growth in consumption gets retarded.

The same is the case with $NO_x$, whose formation during combustion of gasoline or any fuel with air cannot be checked. Next is incomplete combustion of the fuel due to very small time to it in the engine and perfect mixing not possible. Partly burnt hydrocarbon emissions from the exhaust of automobile engines are found to be carcinogenic in nature.

The problem of incomplete combustion and $NO_x$ can be managed by using a catalytic converter in the exhaust. Sulphur compounds, however, poison the catalyst of the converter and so should not be present in the gasoline. This condition is not compatible with TEL (tetra ethyl lead) which in small quantity is doped in gasoline for Octane improvement.

## 21.3 Octane improvement requirement in gasoline engines

The average efficiency of Internal Combustion engine is in the range of 30–45 per cent. Among other parameters, compression ratio is an important factor that has a large influence on efficiency. Higher the ratio the better is the efficiency. Problem with gasoline is its knocking tendency when a higher compression ratio is sought in order to achieve higher thermal efficiency. The knocking tendency of the fuel limits the compression ratio of the gas engine that can be used. Different classes of hydrocarbons have a difference in their tendency towards resistance to knocking. Oil companies carry out blending of different class of hydrocarbons for increasing the octane rating of the fuel. Still, in the past, they could not achieve a reasonable value of octane number till the discovery of TEL an additive to improve the anti-knocking rating of the fuel dramatically was not made.

Addition of TEL in a small quantity became a practice. The harmful effect of the lead led to banning of its use and oil companies were forced to seek other sources of improving the anti-knocking tendency of the gasoline. One is to increase benzene or cyclic compounds in it. Benzene is, however a known carcinogenic material and its content is being limited in the gasoline. Alternatively, MTBE (methyl tertiary butyl ether) and ETBE (ethyl tertiary butyl ether) are being used as additives to improve anti-knocking tendency. MTBE and ETBE are compounds manufactured from the petroleum source but contain oxygen in addition to hydrocarbons. They are termed as oxygenates and their use improves not only anti-knocking tendency but results in the reduction in other vehicular emissions. The oxygenated fuels burn more completely and so reduce carbon monoxide emission up to 20 per cent.

## 21.4 Diesel engine problem, higher emission of respiratory particulate matter

The major problem with diesel is emission of large particulate matter. US, Environmental Protection Agency, EPA is putting increasingly strict exhaust emissions standard for truck and bus engines. EPA has proposed a gradual reduction of PM reduction from 0.1 g/bhp-hr rule in 2002 to 0.01 g/bhp-hr in 2006. Even stricter regulations are being initiated in EU. Use of oxygenate is expected to improve combustion efficiency and hence reduction in PM. In India also under the orders of the Supreme Court strict emission norms are being introduced in a phased manner.

## 21.5 Ethanol as an oxygenate

Ethanol and methanol can serve as oxygenates. Ethanol and MTBE are now the most accepted fuel oxygenates. Compared to MTBE which is petroleum derived and contains 18 per cent oxygen, ethanol is not only renewable but contains 35 per cent oxygen. MTBE is both very water soluble and highly toxic; one teaspoonful being sufficient to contaminate whole water of a large swimming pool. When gasoline is spilled or leaked, it would contaminate groundwater. Use of MTBE is going to receive a set back due to recent findings in USA where drinking water is found contaminated with MTBE in a very large section of population (27 per cent of urban water supply) and the state has been asked to phase put MTBE in gasoline. Attempts were made to get a waiver but it was not granted. This clearly leaves the choice to ethanol. Eleven states in USA have acted to curtail MTBE use. With lower use of light vehicles, the MTBE problem may not be as serious as that in USA, still on economical ground, ethanol deserves preference over MTBE.

## 21.6 Ethanol as an automotive fuel

While the calorific value of ethanol is lower than that of gasoline by 40 per cent it makes up a part by increased efficiency. So far its use as 100 per cent fuel is concerned it has no problem in designing an engine to run on only ethanol. However, for the reason of compatibility as well as availability its use for blending is only being practised. It can be blended both in diesel as well as gasoline. The advantages and problems associated with the blends are summarised in the following paragraphs.

As can be seen from above, ethanol improves the octane number, has a higher volumetric efficiency leading to increased power and has advantages of wider flammability limits and higher flame velocity. It has, however, certain disadvantages: (i) higher aldehyde emissions, (ii) corrosiveness, affecting metallic parts, (iii) higher latent heat of vapourisation causing startability problem, (iv) higher evaporation losses due to higher vapour pressure, and (v) requiring large fuel tank due to lower calorific value. Blends above 15 per cent ethanol would require a few engine modifications to address:

1. Corrosion problem of the metal parts
2. Compatible elastomers for oil seals and rubber components
3. Larger orifice for more flow of fuel through carburettor/injector
4. Retarding ignition timing
5. Increasing compression ratio to take advantage of higher cetane number of ethanol

However, below the 10 per cent value, the disadvantages are not serious and there is no need of modifying the engine, i.e. it would be compatible with the blends.

## 21.7 Ethanol–diesel blends (e-diesel)

In addition to the concern because of reserves of petroleum being limited, the environmental concern is even greater. Diesel generation in general emits large quantity of particulate matter and especially below micron 2.5 which being very small pass the protection system of the body to get lodged in lungs causing reduction in its vital capacity. More seriously than this is the association of the particulate matter with unburnt oil that is potential carcinogenic to human or animals. For this reason, such particles are called respiratory particulate matter and in metro diesel driven vehicles are being phased out. A 15 per cent ethanol blend reduces PM emission; however, the blend provides certain technical problems which are discussed below:

1. The ethanol reduces the flash point of blend to 13°C, i.e. at the level of pure ethanol which is 50°C lower than that of diesel. For the higher ambient temperature of the country, this disadvantage is not desirable and some additive may be required.
2. Blend reduces the lubricity of the fuel and increases the wear of the piston rings and injector. In coming years, the sulphur content of the diesel is expected to be lower to 15 ppm and the lubricity of the blend may get further reduced.
3. Ethanol and diesel fuel do not mix properly. It is found that the presence of water or extreme cold temperature causes the mixture to separate. The fuel mixture is known as a micro-emulsion and is prepared by splash blending in presence of a blending agent. Tolerance of water is influenced by the amount of aromatics level in diesel but generally is of the order of 0.1 per cent. E-diesel owes its commercial viability to the development of the effective emulsifier puranol, invented by Pure Energy Corporation (PEC). Development of more effective emulsifiers is required.
4. The cetane number of the ethanol is just 8 and so reduces the cetane number of diesel on blending.
5. The calorific value of ethanol is 42 per cent lower than that of diesel on volume basis and would decrease the fuel economy and torque and would need higher injector size to obtain the same peak power. This problem is, however, of not much concern for blends lower than 5 per cent.

## 21.8 Gasoline ethanol blend

The gasoline-ethanol blend is more in practice for the reason of the ability of ethanol to increase octane rating of the fuel without adding to pollution or unsustainability. The issue of octane improvement has been discussed earlier. Performance parameters of ethanol blends with gasoline are discussed below.

### 21.8.1 Fuel efficiency

As there is a theoretical decrease in the energy content of gasoline blended with oxygenates, a decrease in mileage, km/l of fuel consumed is expected. No definite data is available to correlate the increase in fuel consumption, but with a blend up to 10 per cent not more than 1–3 per cent reduction in vehicular fuel economy in terms of km/l could be expected in the highway driving. It would be insignificant and will not be noticed. On the contrary in urban use a significant increase in fuel efficiency has been reported.

### 21.8.2 Engine performance and drivability

The higher latent heat of vapourisation of ethanol than that of gasoline is expected to cause startability problem. But 25 per cent blend of ethanol in gasoline is in use in Brazil for the last 25 years without any such problem. The consumption of ethanol in gasoline blend has been more than 10 billion litres there. Ten per cent ethanol blend in gasoline is also in use in USA for the last 18 years and no problem has been encountered as to drivability, etc.

### 21.8.3 Material compatibility

Ethanol is corrosive in nature, absorbs moisture readily and can affect metallic parts (ferrous/nonferrous). However with the 10 per cent ethanol blend the Phillips petroleum study has found no compatibility problem of various components with respect of corrosion tests and swell tests, etc. in fuel systems. The experience of using ethanol blended gases in Brazil and USA shows no significant material problems even with older vehicles whereas newer vehicles are having better materials to fight corrosion like flouroelastomers.

### 21.8.4 Emission issue

One of the major reasons for using blend is reduction in vehicular emission and eliminating the otherwise emission of lead, benzene, butadiene, etc.

### 21.8.5 Hydrocarbon emission

With better combustion, the ethanol blended gasoline provides a reduction in total hydrocarbon emissions though there is a slight increase in the emission of acetaldehyde. The increase in acetaldehyde emission with 5 per cent ethanol blend has been found marginal, 260 mg vs. 233 mg per test cycle. With catalyst converters now being used in vehicles reduces aldehydes level by ten times. And therefore the problem is not considered serious. No limits have been set for aldehydes in ethanol by EU, Brazil or USA as emissions are well within tolerable limits. In fact formaldehyde emissions from MTBE are more and greater degree of concerned from health angle.

### 21.8.6 Carbon monoxide emission

For the same reason as above CO emission also gets reduced as confirmed by many studies.

### 21.8.7 Sulphur dioxide emission

As ethanol does not contain sulphur, a corresponding decrease in $SO_2$ emission results.

### 21.8.8 Carbon-cycle emission

For the ethanol part, it can be taken as zero as it is derived from the plant. Some increase in gasoline emission is likely due to decreased fuel mileage. But in overall consideration there would be decrease in carbon emission.

## 21.9 Standards for ethanol use as fuel blending

Because of low water tolerance of alcohol gasoline blends, ethanol can be blended only in anhydrous form. For 25 per cent blend less than 2 per cent of water can cause separation. Two stroke engines require oil to be mixed with gasoline. Since oil is not properly miscible with gasoline some additive is required to be added to this (Table 21.1).

**Table 21.1** ASTM D4806-9 fuel ethanol specifications.

| Property | Limit |
|---|---|
| Ethanol (vol. %) | 92.1 |
| Water (vol. %) | 1.0 max |
| Methanol (mg/l) | 0.5 max |
| Acetic acid (wt %) | 0.007 |
| Chlorine (mg/l) | 40 max |
| Copper (mg/l) | 0.1 max |
| Denaturants (vol. %) | 1.96–4.76 |

## 21.10 Production of ethanol

In all, three different class of sources can be used:

1. Starch as grain, corn and tubers like cassava
2. Sugar plants (sugar beet or sugar cane)
3. Cellulose plants (general tree and biomass)

## 21.11 Manufacturing process of ethanol

Ethanol production is a very ancient activity linked with making potable alcohol. The liquor containing corn, grapes juice, molasses, etc. are fermented by adding yeast to it in batch fermentators for a number of hours (minimum 40 hours) when fermentation gets completed with no increase in alcohol content. The fermentation process consists of breaking of starch or cellulose chain into individual sugar molecules and then fermenting the sugar into ethanol and carbon dioxide. The major reaction is depicted below. The equations show that fermentation of glucose/sugar to ethanol is energy efficient, about 93 per cent of the feed energy is converted as ethanol and only a small amount is taken by fermenting organism (yeast).

| | | |
|---|---|---|
| Hydrolysis | $[C_6H_{10}O_5]_n + nH_2O \rightarrow nC_6H_{12}O_6$ (glucose) | |
| Fermentation | $C_6H_{12}O_6 \rightarrow$ | $2C_2H_5OH + 2CO_2$ |
| Energy balance | Glucose $\rightarrow$ | 2 ethanol + 75 KJ |
| | 180 g | $2 \times 46$ g |
| | 2.82 MJ | $2 \times 1.37$ MJ |

### 21.11.1 Making anhydrous ethanol

By fermentation alone not more than 10 per cent ethanol content can be achieved, whereas the requirement for potable or industry is of getting over 95 per cent purity. The traditional method is distilling the fermented liquor which can provide a purity up to 95 per cent. Water in ethanol is undesirable in its use in gasoline blend and a purity over 99 per cent (i.e. anhydrous alcohol) is required. Ethanol forms constant boiling mixture with water at 95.6 per cent that does not allow simple distillation to meet the purpose. As a solution to the problem, azeotrophic distillation through solvent benzene or cyclohexane is used. Azeotrophic distillation, however, increases production cost of ethanol considerably. The cost effective solution is found through the use of molecular sieve to eliminate water by an adsorbent, properly known as pressure swing adsorption molecular sieve dehydration technology (MSDH). It uses a synthetic adsorbent to dehydrate alcohol and results into high level of dryness with low energy requirement. Use of vapour phase adsorption has resulted into further energy saving in the process.

Fermented wash with approx. 8 per cent v/v ethanol from the wash holding tank is fed to the top of the degasifying column after preheating and spent stillage cooler. Overhead vapour of approximate 40 per cent w/w from the degasifying column is then fed to the bottom of the heads column. Impure spirit with approximate 95 per cent v/v is removed from the vent condenser of the heads column. Heads column bottoms are fed to the alcohol column for recovery of alcohol.

The wash column is heated through the forced circulation reboiler with the condensing vapours from the rectifying column, which is operated under pressure. Analyser column vapours are condensed and fed to an extractive distillation column. This column is operated with high dilution to enable the removal of fusel oils. Vapours are condensed and sent to the recovery column for alcohol recovery.

The alcohol water stream from the bottom of the extractive distillation column is fed to the rectifying column. The rectifier vapours are used to heat the analyser by using the pressure cascading technique. Ethanol (concentration of 96 per cent v/v) is removed from the top three plates and fed to the demethyliser column for separating methanol. The product rectified spirit (RS) is removed from the bottom of the methanol column and cooled in the product cooler. Anhydrous alcohol is produced from 96 per cent RS by molecular sieve technology. Anhydrous ethanol with purity above 99.8–99.9 is produced in the system, using vapour phase adsorption with pressure swing for regeneration. This is the most economical technology for producing anhydrous alcohol.

## 21.12 Feedstock–sugarcane–sugar route technology and economics of production

### 21.12.1 Feedstock

The major source of ethanol production in the country is via sugarcane–sugarmolasses route. This provides better economy by sale of sugar; molasses becomes the by-product of sugar (Fig. 21.1).

### 21.12.2 Through sugar beet

In European countries sugar beet is preferred. Sugar beet has certain advantages over sugarcane. The advantages are: lower cycle of crop production, higher yield, high tolerance of wide range of climatic variation, low water and fertiliser requirement (compared to sugar cane, sugar beet requires 35–40 per cent water and fertilisers). From Table 21.2 it is clear that ethanol yield is higher per year per unit of land even taking only one crop and (no credit for other crops) which will be there in case of sugar beet. Harvesting of sugar beet is also easier as well as requires lower energy for juice extraction. The pulp can be used for cattle field for steam generation.

**Table 21.2** Comparison of cane and sugar beet

| Properties | Cane | Sugar beet |
|---|---|---|
| Cycle of crop | 10–11 months | 5–6 months |
| Yield per acre | 25–30 tons | 35–40 tons |
| Sugar content on weight | 12–16% | 14–18% |
| Sugar yield | 3.0–4.8 tons/acre year | 4.9–7.2 tons/acre year |
| Ethanol yield (100%) | 1700–2700 l/acre/year | 2800–4100 l/acre/yr (with one cycle/yr) |

Considering the surplus sugar production in the country it will provide an outlet for the cane production if some sugar is diverted to ethanol production. A part of juice can be directly converted into ethanol thus saving energy and achieving higher yield and reduction in spent wash.

### 21.12.3 Economics of production

#### *General*

The major factors that affect the ethanol cost are: the yield of sugarcane and cycle of production, the sugar contents in the juice, efficiency in juice extraction as well as in fermentation, and lastly utilisation of waste. Sugarcane production requires long time as well as high irrigation and chemical fertiliser. This increases the cost of production and puts some question on its competitiveness with other crops.

A lower sugarcane content affects greatly the efficiency of farm production as it provides lower tonnage of sugar for the same inputs 'irrigation, fertiliser and labour'. A lower sugar content also results in higher extraction cost per tonne of sugar extracted. Next is their efficiency in extracting the juice. Some of the sugar remains in the bagasse.

A higher level of extraction, however, increases the power cost and the effort reaches a trade-off. A higher level of extraction obviously reduces the cost of juice and therefore cost of sugar/ethanol.

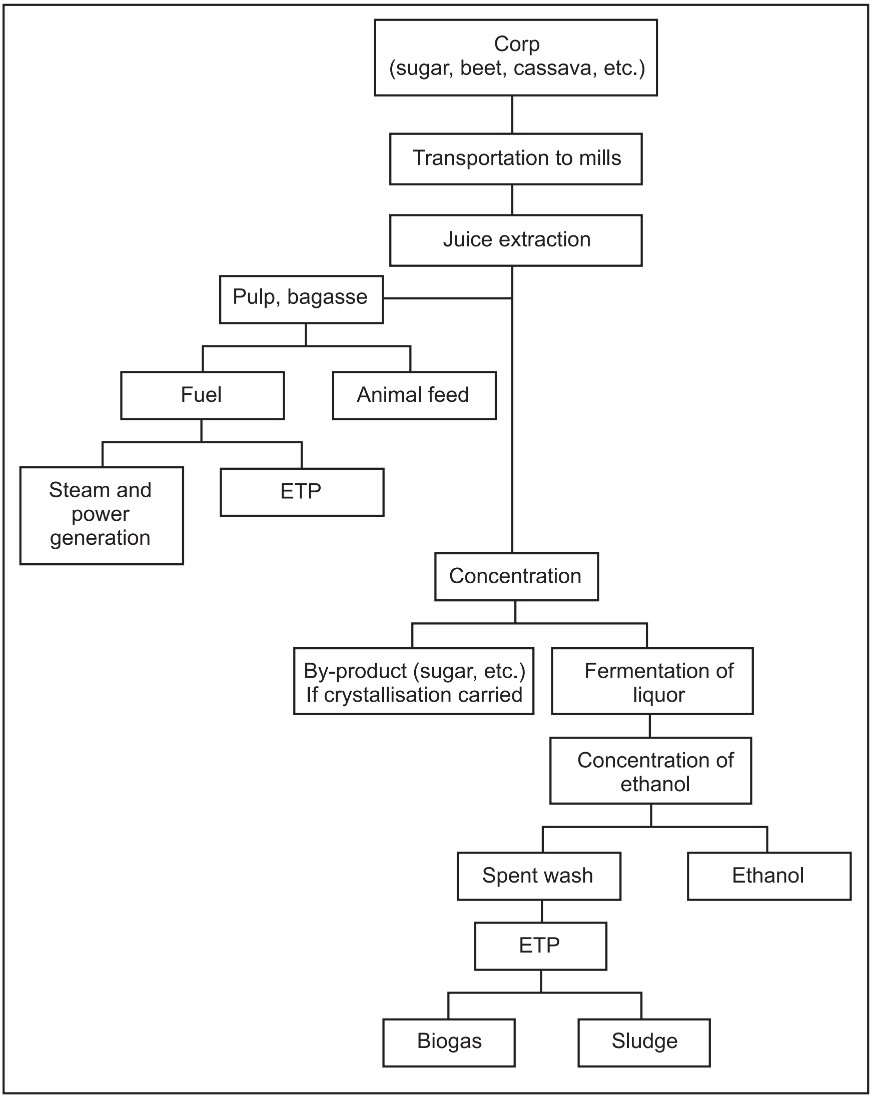



**Figure 21.1 Sugarcane–sugarmolasses route**

Presently, the fermentation does not provide alcohol content above 10 per cent and lot of energy is wasted in removing the balance water to get an hydrous alcohol necessary for blending in gasoline. A higher level of alcohol by fermentation would automatically reduce the cost of purification.

Two major waste products are generated in the ethanol production from sugarcane:

1. Bagasse
2. Spent wash

Bagasse is utilised presently for boiler fuel needed for steam rising; while spent wash is a effluent which requires treatment for COD removal before discharge into the land or river. It is possible through anaerobic digestion to utilise the spent wash in production of two valuable commodities—one methane rich fuel gas and another nutrient rich biosludge suitable for soil nutrition. The gas production can be sufficient to meet the fuel requirement as well as power for electric derives through cogeneration.

## 21.12.4 Sugarcane–molasses–ethanol route

Cost of molasses varies widely across the different states and in the last 6 years it has been as low as Rs. 50/- per ton and as high as Rs. 2000/- per ton. The sizeable part in the cost is central excise duty, sales tax, transportation cost, etc. and the statutory controlled sugarcane and sugar prices, as well as free sale prices coupled with the release of sugar in the market. If we assume that molasses cost Rs. 1000/- per ton the feed stock cost will be Rs. 4.5 per litre of ethanol with production of 220 litres ethanol per tonne of molasses. The raw material cost should not represent more than 50 per cent cost of the ethanol production in general and on that basis the ethanol cost would work out less than Rs. 9/- per litre and would be quite competitive to the present imported cost of gasoline around Rs. 10–12 per litre.

### *Assumptions*

1. Recovery of 220 litres of anhydrous ethanol from one ton of molasses.
2. Molasses price Rs. 1000 per ton.
3. Annual production of ethanol @30,000 litres per day and 300 working days = 90000 litre/year.
4. Alcohol plant assumed to be fully depreciated so capital related charges ignored except that of putting up the facility of making anhydrous alcohol via molecular sieve.
5. Life of molecular sieve assumed to be 5 years and cost = 3000 kg × Rs. 250/kg = Rs 7,50,000 average cost per year Rs. 1,50,000. Cost/litre of ethanol = Rs 5.
6. Power cost of Rs. 4.50/kwh and rice husk cost of Rs. 500/MT with steam raising @ 3T/T of rice husk.
7. Biogas generation can provide enough energy to meet all energy demand but it has not been taken into account.
8. No taxes (excise or sales, etc.) on inputs considered.

## 21.13 Starch-based alcohol production

### 21.13.1 Process

Alcohols are produced from a large number of different starch crops as barley, wheat, corn, potato, sorghum, etc. The conversion of starch into alcohol follows the same process of fermentation and distillation as that of sugarcane. The difference lies in additional two steps, namely,

1. Milling of the corn
2. Removal of by-products, as DDGS, corn oil, corn gum, etc.

Milling of the corn is an energy intensive step and is carried by one of the two main processes:

1. Wet-milling
2. Dry grinding

Wet milling plants are capital intensive but produce high valued by-products whereas dry grind plants cost less but provide lower valued products. Corn contains some cellulose which does not ferment. A residue called dried distillers grains and solubles (DDGS) is obtained. Presently one bushel of corn gives 2.5 gallons of ethanol, 17 lbs of DDGS and 19 lbs of $CO_2$. DDGS utilisation/disposal presents few problems. The present usage is animal feed but can be converted into high valued products also. The efficiency of ethanol conversion would improve if the following two major technological developments are used:

1. Use of enzymes produced by solid state fermentation (SSF), which can breakdown cellulose part also increasing the yield from 2.5 gallons/bu (maxim 2.8 gallon/bu) to 3.52 gallons/bu. This also reduces the DDGS from 17 lbs to 7 lbs/bu and increase its protein content.
2. Use of high temperature yeast as Thermosac capable to operate at 35–40°C, producing 18–20 per cent ethanol.

### 21.13.2 Sweet sorghum as a feedstock

At present, two-thirds of world sugar production is obtained from sugarcane and one third from sugar beet. These two crops are not in competition, but complementary, being cultivated for their specific requirements in two different climatic belts. In contrast, sweet sorghum can be cultivated in temperate and tropical regions, increasing its potential benefits. Other crops that can yield oligosaccharides (potatoes, cereals, grapes, etc.) are generally not much utilised for bioethanol production (with the exception of corn in the USA).

However, particular varieties of sweet sorghum recently developed in China, the USA, and the EU have very attractive and economically promising characteristics. Sweet sorghum can be grown in temperate and tropical regions.

Sweet sorghum produces a very high yield in terms of grains, sugar, lignocellulosic biomass (on average a total of 30 dry tons/ha per year) plantations need less seed than for other crops: 15 kg/ha compared with 40 kg/ha for corn or 150 kg/ha for wheat.

## 21.14 Bioethanol

### 21.14.1 Biomass for bioethanol

Ethanol made from cellulosic biomass is called bioethanol. A major challenge is developing biocatalysts capable of fermenting lignocellulosic biomass for efficient industrial application. In the coming years it is believed that cellulosic biomass will be the largest source of bioethanol. The broad category of biomass for the production of ethanol includes agricultural crops and residues and wood. Biomass resources are abundant and have multiple application potential. Among the various competing processes, bioethanol from lignocellulosic biomass appears to have near-term economic potential. The crops residues such as rice straw, bagasse, etc. are not currently used to derive desired economic and environmental benefits and thus they could be important resource bases for bioethanol production. Table 21.3 indicates potential of such biomass for ethanol production.

**Table 21.3** Potential for ethanol from cellulosic matter

| Feedstock | Gallons ethanol/dry ton |
|---|---|
| Bagasse | 112 |
| Corn stover | 113 |
| Rice straw | 110 |
| Forest thinnings | 82 |
| Hardwood sawdust | 101 |
| Mixed paper | 116 |

### 21.14.2 Review of technologies for manufacture of bioethanol

The degree of complexity and feasibility of biomass conversion to ethanol depends on the nature of the feedstock. The three largest components of the biomass sources are cellulose, hemicellulose, and lignin ranges of which are presented in Table 21.4. Ranges of sugar content in hardwoods, softwoods, and agricultural residues are provided in Table 21.5.

**Table 21.4** Typical levels of cellulose, hemicellulose and lignin in biomass

| Component | Per cent dry weight |
|---|---|
| Cellulose | 40–60% |
| Hemicellulose | 20–40% |
| Lignin | 10–25% |

**Table 21.5** Sugar and ash composition of various biomass feedstock (weight per cent)

| Material | Sugars | Lignin | Ash |
|---|---|---|---|
| Hardwoods | 57–78% | 15–28% | 0.3–1.0% |
| Softwoods | 49–69% | 24–27% | 0.1–0.4% |
| Agri residues | 42–81% | 11–29% | 2–18% |

Lignin remains as residual material after the sugars in biomass have been fermented to ethanol. Economic use of this by-products is critical to the financial feasibility of biomass-to-ethanol technology (Fig. 21.2).

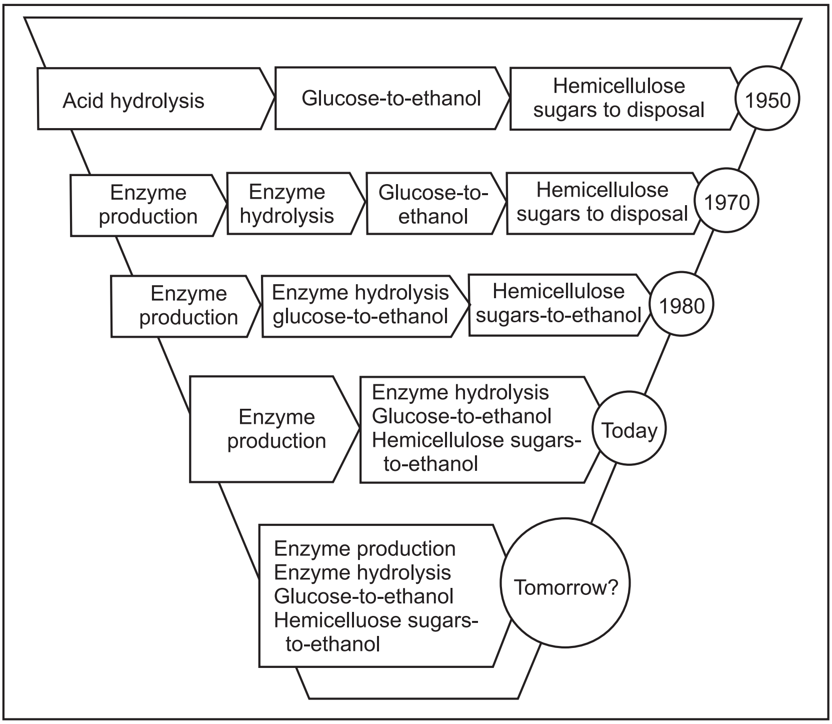



**Figure 21.2** Review of technologies for manufacture of bioethanol over the years

## 21.15 Developments in bioethanol production technologies

### 21.15.1 Process steps

There are four basic steps in converting biomass to bioethanol:

1. Producing biomass results in the fixing of atmospheric carbon dioxide into organic carbon.
2. Converting this biomass to a usable fermentation feedstock (typically some form of sugar) can be achieved using a variety of different process technologies. These processes for fermentation feedstock production constitute the critical differences among all of the bioethanol technology options.
3. Fermenting the biomass intermediates using biocatalysts (micro-organisms including yeast and bacteria) to produce ethanol is probably the oldest form of biotechnology developed by humankind.
4. Processing the fermentation product yields fuel-grade ethanol and by-products that can be used to produce other fuels, chemicals, heat and/or electricity.

### 21.15.2 Technologies

There are four technologies for bioethanol production as given below:

1. Concentrated acid hydrolysis
2. Dilute acid hydrolysis
3. Enzymatic hydrolysis
4. Biomass gasification and fermentation

The first three are based on producing sugars from biomass and then fermenting the sugars to ethanol. The fourth is a very different approach involving thermal processing of biomass to gaseous hydrogen and carbon monoxide, followed by fermentation to ethanol.

#### *Concentrated acid hydrolysis*

This process is based on concentrated acid decrystallisation of cellulose followed by dilute acid hydrolysis to sugars. Separation of acid from sugars, acid recovery, and acid reconcentration are critical unit operations. Fermentation converts sugars to ethanol. The concentrated sulphuric acid process has been commercialised in the past, particularly in the former Soviet Union and Japan. However, these processes were only successful during times of national crisis, when economic competitiveness of ethanol production could be ignored. They cannot be economical because of the high volumes of acid required. Improvements in acid sugar separation and recovery have opened the door for commercial application. Two companies in the United States (Arkenol and Masada) are currently working with DOE and NREL to commercialise this technology. Arkenol holds a series of patents on the use of concentrated acid to produce ethanol.

They are currently working with DOE to establish a commercial facility that will convert rice straw to ethanol. Arkenol plans to take advantage of opportunities for obtaining rice straw a cheap feedstock in the face of new regulations that would restrict the current practice of open field burning of rice straw. Arkenol's technology further improves the economics of raw straw conversion by allowing for the recovery and purification of silica present in the straw. NREL is working with Arkenol to develop a recombinant *Zymomonas mobilis* strain for the project. The facility is located in Sacramento County.

Masada resource group holds several patents related to municipal solid waste (MSW)-to-ethanol conversion. DOE and NREL have been working with Masada to support their MSW-to-ethanol plant, which is located in Middletown, NY. The plant will process the lignocellulosic fraction of municipal solid waste into ethanol using technology based on concentrated sulphuric acid process. The robustness of this process makes it well suited to complex and highly variable feedstocks like municipal solid waste to take advantage of relatively high tipping fees available in the area for collection and disposal of municipal solid waste.

### *Dilute acid hydrolysis*

Hydrolysis occurs in two stages to maximise sugar yields from the hemicellulose and cellulose fractions of biomass. The first stage is operated under milder conditions to hydrolyse hemicellulose, while the second stage is optimised to hydrolyse the more resistant cellulose fraction. Liquid hydrolysates are recovered from each stage, neutralised, and fermented to ethanol.

There is quite a bit of industrial experience with the dilute acid process. Germany, Japan, and Russia have operated dilute acid hydrolysis percolation plants off and on over the past 50 years. However, these percolation designs would not survive in a competitive market situation. Today, companies are beginning to look at commercial opportunities for this technology, which combine recent improvements and niche opportunities to solve environmental problems.

BC International (BCI) and the DOE have formed a cost-shared partnership to develop a biomass-to-ethanol plant. The facility will initially produce 20 million gallons per year of ethanol. BCI has utilized an existing ethanol plant located in Jennings, LA. Dilute acid hydrolysis will be used to recover sugar from bagasse, the waste left over after sugar cane processing.

A proprietary, genetically engineered organism will ferment the sugars from bagasse to ethanol.

Tembec and Georgia Pacific are operating sulphite pulp mills in North America, which utilise a dilute acid hydrolysis process to dissolve hemicellulose and lignin from wood, and produce speciality cellulose pulp. The hexose sugars in the spent sulphite liquor are fermented to ethanol. The lignin is either burnt to generate process steam or converted to value-added products such as dispersing agents, animal feed binders, concrete additives, drilling mud additives, and soil stabiliser.

### *Enzymatic hydrolysis*

The first application of enzymes to wood hydrolysis in an ethanol process was to simply replace the cellulose acid hydrolysis step with a cellulose enzyme hydrolysis step. This is called separate hydrolysis and fermentation. An important process modification made for the enzymatic hydrolysis of biomass was the introduction of simultaneous saccharification and fermentation (SSF), which has recently been improved to include the co-fermentation of multiple sugar substrates. In the SSF process, cellulase and fermenting microbes are combined. As sugars are produced, the fermentative organisms convert them to ethanol. Enzymatic hydrolysis will be used in Iogen/Petro Canada's Ottawa, Canada project and is being explored for BCI's Gridely project. The current high cost of cellulase enzymes is the key barrier to economical production of bioethanol from lignocellulosic material, research is on to achieve a tenfold reduction in the cost of these enzymes.

### *Cellulase enzyme research*

The goal is to reduce the cost of using cellulase enzymes in the bioethanol process by employing cutting-edge and efficient biochemical technologies. The current estimate for cellulase ranges from 30 to 50 cents per gallon of ethanol produced. The objective is to reduce cellulase cost to less than 5 cents per gallon of ethanol. This requires a tenfold increase in specific activity or production efficiency or some combination thereof. Nearer-term goals include a threefold increase in cellulase-specific activity (relative to the Trichoderma reesei system) by FY 2005. This may be possible by genetic manipulation of microbes.

### *Biomass gasification and fermentation*

Biomass can be converted to synthesis gas (consisting primarily of carbon monoxide, carbon dioxide, and hydrogen) via a high temperature gasification process. Anaerobic bacteria are then used to convert the synthesis gas into ethanol. Bioresource Engineering Inc. has developed synthesis gas fermentation technology that can be used to produce ethanol from cellulosic wastes with high yields and rates. The feasibility of the technology has been demonstrated, and plans are under way to pilot the technology as a first step toward commercialisation.

The conversion of a waste stream, the disposal of which is costly, into a valuable fuel adds both environmental and economic incentives. The yields can be high because all of the raw material, except the ash and metal, is converted to ethanol. BRI has developed bioreactor systems for fermentation that results in retention times of only a few minutes at atmospheric pressure and less than a minute at elevated pressure. These retention times result in very economical equipment costs. The biocatalyst is automatically regenerated by slow growth of the bacteria in the reactor.

### 21.15.3 Development of microbes

Micro-organisms that ferment sugars to ethanol include yeasts and bacteria. Research has focused on expanding the range and efficiency of the organisms used to convert sugar to ethanol. Breakthroughs in fermentation technology in the past decade lead to commercialisation of biomass conversion technology. For most of this century, researchers assumed that many of the sugars contained in biomass were not fermentable particularly those contained in hemicellulose. This meant that as much as 25 per cent of the sugars in biomass were out of bounds as far as ethanol production was concerned. In the 1970s and 80s, microbiologists discovered microbes that could ferment these sugars, albeit slowly and inefficiently. With the advent of new tools in the emerging field of biotechnology, researchers at DOE labs and at universities across USA, have succeeded in producing several new strains of yeast and bacteria (E. coli, Zymomonas, Saccharomyces) that exhibit varying degrees of ability to ferment the full spectrum of available sugars to ethanol. Today's ethanol producers are turning their attention to corn fibre—the shell of the kernel as a source of additional sugars for ethanol production. But, corn fibre, like other forms of biomass, contains sugars that are not fermentable by today's industrial fermentation organisms. Research is on to tailor new microbes that can ferment these specific sugars.

### 21.15.4 Raw materials for making bioethanol

Ethanol producers in the United States produce around 1.5 billion gallons of ethanol each year, mostly derived from corn. As demand for ethanol increases, other biomass resources, such as agricultural and forestry wastes, municipal solid wastes, industrial wastes, and crops grown solely for energy purposes, will be used to make ethanol. Research activities over the past 20 years have developed technology to convert these feedstocks to ethanol. Fuel ethanol is currently produced from the easily fermented sugars and starches in grain and food processing wastes. Soon, new technologies will be economically viable for converting plant fibre to ethanol. A portion of the agricultural and forestry residues (corn stover, stalks, leaves, branches) which are presently burned or left in the field may therefore be harvested for biofuel production. There will be many benefits by connecting the established corn ethanol industry with the emerging technologies that produce ethanol from agricultural wastes and other types of biomass.

## 21.15.5 Meeting the ethanol demand for blending

The ethanol demand for blending can be calculated from the plan projection of the future growth in gasoline use. Tables 21.6, 21.7 and 21.8 provide the figures for the tenth plan together with the availability.

**Table 21.6** Ethanol demand and supply for blending in gasoline.

| Year | Gasoline demand (MMT) | Ethanol demand (Th Kl) | Molasses production (MMT) | Molasses (Th Kl) | Ethanol production | | | Utilisation of ethanol | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Cane (Th Kl) | Total (Th Kl) | Potable (Th Kl) | Industry (Th Kl) | Balance (Th Kl) |
| 2001–02 | 7.07 | 416.14 | 8.77 | 1775 | 0 | 1775 | 648 | 600 | 527 |
| 2006–07 | 10.07 | 592.72 | 11.36 | 2300 | 1485 | 3785 | 765 | 711 | 2309 |
| 2011–12 | 12.85 | 756.35 | 11.36 | 2300 | 1485 | 3785 | 887 | 844 | 2054 |
| 2016–17 | 16.4 | 965.30 | 11.36 | 2300 | 1485 | 3785 | 1028 | 1003 | 1754 |

**Notes:**

1. Area under cane cultivation is expected to increase from 4.36 mha in 2001–02 to 4.96 in 2006–07 which would add additional cane production of around 50 MMT.
2. About 30 per cent of cane goes for making gur and khandsari. If there is no additional increase in khandsari demand, sugar and molasses production would increase.
3. The present distiller capacity is for 2900 Th Kl of ethanol and looks to be sufficient for 5 per cent blend till 12th plan.
4. A growth of 3 per cent in potable use and a 3.5 per cent in chemical and other use has been taken/assumed.

**Table 21.7** Alcohol production from molasses and use (in million litre).

| Alcohol year | Molasses production MMT | Production of alcohol (ml) | Industrial use (ml) | Potable use (ml) | Other uses (ml) | Surplus availability of alcohol (ml) |
|---|---|---|---|---|---|---|
| 1998–99 | 7.00 | 1411.8 | 534.4 | 584.0 | 55.2 | 238.2 |
| 1999–00 | 8.02 | 1654.0 | 518.9 | 622.7 | 57.6 | 455.8 |
| 2000–01 | 8.33 | 1685.9 | 529.3 | 635.1 | 58.8 | 462.7 |
| 2001–02 | 8.77 | 1775.2 | 539.8 | 647.8 | 59.9 | 527.7 |
| 2002–03 | 9.23 | 1869.7 | 550.5 | 660.7 | 61.0 | 597.5 |
| 2003–04 | 9.73 | 1969.2 | 578.0 | 693.7 | 70.0 | 627.5 |
| 2004–05 | 10.24 | 2074.5 | 606.9 | 728.3 | 73.5 | 665.8 |
| 2005–06 | 10.79 | 2187.0 | 619.0 | 746.5 | 77.2 | 742.3 |
| 2006–07 | 11.36 | 2300.4 | 631.4 | 765.2 | 81.0 | 822.8 |

**Table 21.8** Potential of ethanol production from sugarcane

| Year | Area under cane | Cane production | Cane utilisation | | | Sugar production | | Additional alcohol production (in million litre) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Sugar | Gur and khand | Seed and chew | Target | Revised production | From additional molasses production | Additional cane available for alcohol |
| 2002–03 | 4.36 | 309.9 | 181 | 92.0 | 37 | 182 | 192 | 69 | 475 |
| 2003–04 | 4.53 | 321.6 | 188 | 95.6 | 38 | 192 | 202 | 99 | 795 |
| 2004–05 | 4.63 | 333.3 | 195 | 98.3 | 40 | 199 | 212 | 128 | 1000 |
| 2005–06 | 4.79 | 345.1 | 202 | 102.1 | 41 | 206 | 223 | 168 | 1222 |
| 2006–07 | 4.96 | 356.8 | 209 | 104.8 | 43 | 213 | 233 | 198 | 1485 |

As per the All India Distillers Association, the present installed capacity of alcohol production in the country is 2900 million litres. With the present availability of molasses to the tune of 9 million tonnes the alcohol production is around 1800 million litres. Out of which around 600 million litres is surplus after meeting the demand of industrial use (540 million litres) and potable use (650 million litres). This is capable of providing a 5 per cent blend to the gasoline. The present consumption of gasoline is estimated at 8.5 million tonnes requiring 502 million litres for 5 per cent blend. The industry expects that the present capacity is able to meet the blending requirement of the gasoline till the end of the Tenth plan with the terminal years of gasoline consumption at 11.6 million tons needing 682 million litres of ethanol for blending, where 823 million litres will be surplus from the production of 2300 million litres of alcohol.

Decision has already been taken to make it compulsory for a 5 per cent blend of ethanol in gasoline. Since there is a surplus production of sugar and export not giving much value addition it will not be irrational to convert sugar to alcohol or directly came to alcohol in much more proportion than being carried now. By this a 10 per cent blend of ethanol with gasoline can be maintained for considerable period. Apart from sugarcane, other agroproducts including grains can be used for fermentation. Taking the crop yield in account, sugarcane is the best choice as it is the crop having the highest efficiency of photosynthesis and provide a possibility of 1200 gallons of 99 per cent alcohol from a acre. Potato provides the next highest yield of alcohol on unit area of land; 300 gallons per acre.

From Table 21.8 it is clear that for meeting 5 per cent blending demand, the ethanol capacity in the country is sufficient. For higher blend and till the demand stabilises, the crop productivity or use of biomass into converting to alcohol would be much more needed. The government has taken the decision to make the 5 per cent blending in gasoline as mandatory in phased manner. As stated above, the industry can easily meet the requirement if the land is not diverted from cane production.

### 21.15.6 Economics of alcohol production

#### *From sugarcane*

A ton of sugarcane, on an average, would provide 110 kg of fermentable sugar in the juice. If all the sugar juice is fermented directly, the ethanol yield will be 70 litres taking a sugar loss of 2 per cent in spent wash and specific gravity of ethanol as 0.79. The present price of sugarcane as fixed by Centre under the minimum statutory price stands at Rs. 695 per ton with 8.5 per cent recovery. At higher recovery which is the case always, the effective price comes to Rs. 900 per ton if state governments does not add further cost to it. For example, the UP state has added the statutory price by Rs. 45 per ton on the Centre's price of Rs. 695. Therefore the feed stock price itself comes to Rs. 900.70 = Rs. 13 per litre of ethanol. A minimum of Rs. 2 per litre would be the conversion cost i.e. salary and wages of the operational staff. In other words, direct conversion of sugar juice to ethanol will cost more than Rs. 20 per litre, if we add the capital related charges of investment, profit to the manufacturer, energy cost of making anhydrous alcohol, transport, marketing, blending, etc. This may not be financially viable with present ex-factory cost of gasoline. To make it viable following options are available:

1. Sugarcane prices are decontrolled and left for the market to decide. This may result into cane prices lower than Rs. 500 per ton.

2. Combining with sugar production so that major part of cane cost is off-loaded to sugar. This is the present situation also where all the ethanol production from sugarcane is coming through molasses, a by-product in sugar production. A ton of sugarcane produces 100 kg of sugar as well as 40 kg of molasses the latter will produce around 10 litres of ethanol. Even if sugar is sold at Rs. 10 per kg it will be sufficient to pay all the cost of the sugarcane.
3. Use of by-products bagasse and spent wash very efficiently. The spent wash which is produced in large quantity (around 15 litre for 1 litre of ethanol produced) can be subjected to anaerobic digestion which not only removes its BOD and COD but will also provide valuable biogas (60 per cent methane) which can meet 2/3rd of energy cost of making anhydrous alcohol through conventional route. Using absorption or membrane technology of drying alcohol above 95 per cent purity, the biogas generation would be sufficient for all its energy demand (if short by any margin, the same could be made from the bagasse based cogeneration facility). The bagasse which is left after crushing can provide electricity through efficient cogeneration. As per an estimate, a cane crushing mill with 455 tph crushing capacity can generate 44 MW of power. This comes to about 97 kWh/T of cane crushed. At a Rs. 2 kWh rate of power exported to grid the earning will be far sufficient to meet the cane prices even after meeting the capital rated charges of installing the power generation facility. To realise the energy efficiency as stated above, the following would have to be set up having the magnitude of the capital investments as indicated:
   (a) Molecular sieve costing around Rs. 2–2.5 crore for 30 kld plant
   (b) Anaerobic biogas production costing Rs. 4–5 crore
   (c) Steam and power generation plant (cogeneration) costing around Rs 3 crore/MW

Fortunately, apart from a low payback period for return in investments, there are several sources of getting finance for setting up the facilities above (to increase efficiency):

1. Assistance from Asian Development Bank, KfW, Germany, JBIC, Japan
2. Assistance from IREDA under renewable energy plan
3. Carbon credit of nearly \$10/T of carbon saved under CDM of the Kyoto protocol

## *From other feedstocks*

The other major source can be corn, sugarbeet, potatoes, etc. Depending on the starch content's in the feedstock, the yield of ethanol would vary. Taking corn, it can be at 2.75 ton of grains per kilolitre of ethanol. The feedstock cost at Rs. 7 per kg itself would cost Rs. 20 in one litre of ethanol so produced. The sale of the residue, (i.e. dried distillers grains and solubles which is produced in the quantity of 0.56 kg per litre of ethanol produced would fetch a maximum of Rs. 3.5 @ Rs. 6 per kg of residue unless the latter is converted to more value added products. Thus the feedstock price after taking the credit of the DDGS sale would not be lower than Rs. 16.5 per litre. The spoiled grain available in large quantity (2–5 lakhs tons per year from FCI) would certainly make a very cheap alcohol. For others, it is the market price that will determine the economics. Generally foodgrain price will be dictated by its use for human consumption which, in turn, will be subjected to prices across other grains and alternatives.

### 21.15.7 R&D work

While a boundary can be drawn to limit R&D activities in the area of ethanol production from agro-crops or biomass in general, but for short-term requirement, the following areas of research and development should be stressed mainly towards the compatibility of the use of blends in existing engines.

#### *Ethanol–gasoline blend*

1. Performance of engine and corrosion of ethanol gasoline blend at higher ethanol percentage above 10 per cent. Because of the low water tolerance of alcohol–gasoline blends, anhydrous ethanol must be used and great care must be exercised to avoid water contamination. For 25 per cent alcohol blend, less than 2 per cent of water will cause separation. Ethanol can also be used in modified engines, specifically designed and manufactured to operate on ethanol fuel, and will generally be more efficient than modified gasoline engines.
2. Most conventional vehicles on the road today can use E10 (a 10 per cent ethanol–90 per cent gasoline blend also known as gasohol) without any special modifications. However, auto manufacturers are also producing vehicles that are specially modified to run on a higher percentage of ethanol. Generally, the use of ethanol blending reduces the harmful emissions like CO, $CO_2$ and hydrocarbons. However, additional studies are required to understand potential emissions benefits for all engine models and driving cycles. Effect on exhaust treatment devices using ethanol blending should also be established. The main mechanical differences between ethanol and gasoline

vehicles lie in the engine calibration and the fuel management system. Ethanol vehicles come with a special computerised system that monitors the ethanol/gasoline ratio of the fuel, optimises performance, and adjusts emissions control devices. Ethanol may also corrode certain materials that are commonly used in automobile parts, such as rubber and plastic. Components that come in contact with the fuel, such as piston rings, engine block, and valve seals, must be made of ethanol-compatible materials.

3. Suitable additive for ethanol gasoline blend to be used in two stroke engines. The use of ethanol in specially designed two-cycle engines has been demonstrated on a limited basis. The problem of using ethanol in these engines is that the ethanol does not blend well with lubricating oil. To get around this problem, research is under way to find lubricating oils that are not affected by ethanol engines. The study on in-use vehicle must also be considered because they are having totally different configuration compared to new generation vehicles.
4. Aldehyde emission: Aldehyde emissions from ethanol blends are generally higher than those from gasoline. Formaldehyde, the major constituent in aldehyde emissions, is a suspected carcinogen. However, the catalytic converters used vehicles reduce aldehyde emissions to near the level produced when unblended gasoline is combusted. The Royal Society of Canada has concluded that any increases are minute, and harmful effects are remote.

## *Ethanol–diesel blends*

1. E-diesel cannot be safely handled like conventional diesel but must be handled like gasoline. This may necessitate some modifications to storage and handling equipment, as well as vehicle fuel systems. Stability is much less of a concern for micro-emulsions as these have proven stable for extended periods. However, stability of e-diesel micro-emulsions under a range of storage conditions will need to be demonstrated. Emulsifiers are known to extend the stability of ethanol-diesel blends to lower temperatures at ethanol blending levels as high as 15 per cent or even 20 per cent in conventional diesel. Detailed data on the efficacy of emulsifiers as a function of temperature and fuel aromatic content do not appear to be publicly available and most manufacturers have not optimised emulsifier. A large body of test data acquired in close cooperation with the OEM’s will be necessary to address this issue. Development of better emulsifier for ethanol diesel blend.

2. Lubricity of e-diesel: Lubricity is the ability of the fuel to lubricate metal surfaces and is relevant to wear in fuel pumps and other engine components that are lubricated by the fuel. Severely hydrotreated, ultralow sulphur diesel fuels as well as Fischer–Tropsch diesel fuels tend to have low lubricity. This can be remedied through the use of a lubricity additive or by blending with higher lubricity components. Ethanol is not manufacturers claim that the emulsifier itself can impart improved lubricity. This would seem to be substantiated by data made public by PEC that shows premium lubricity properties (i.e. HFRR of less than 300 micron and SLBOCLE of more than 5200 g [jht1]). Better quantification of the effect of e-diesel on fuel lubricity for both conventional and ultralow sulphur fuels is needed. The inclusion of lubricity in an e-diesel standard may be desirable.
3. Other problem of e-diesel: Concerns are expressed related to engine performance using e-diesel. These include the idea that the solvency effect of ethanol might loosen deposits in older vehicles causing breakdowns. Another concern is that because of e-diesel's higher volatility, there may be a greater incidence of pump and injector cavitation, leading to increased wear and hot restart problems. The lower energy content may require changes to governing strategy to prevent stalling under certain conditions such as steep grades, high temperature, and altitude. While some of these concerns may prove to be unfounded, they will require investigation.

## *Ethanol production from biomass*

1. Development of more energy efficient and economical process for fermenting cellulose materials into ethanol. In the coming years it is believed that cellulosic biomass will be the largest source of bioethanol. The broad category of biomass for the production of ethanol includes agricultural crops and residues and wood. Biomass resources are abundant and have multiple application potential. Among the various competing processes, bioethanol from lignocellulosic biomass appears to have nearterm economic potential. The crops residues such as rice straw, bagasse, etc. are not currently used to derive desired economic and environmental benefits and thus they could be important resource bases for bioethanol. A major challenge is developing biocatalysts capable of fermenting lignocellulosic biomass for efficient industrial application. Some narration on the possibility would be in order which would also highlight the need of research in the area.
2. Study on gasification route to produce ethanol from biomass: Compared to enzymatic route of making alcohol, chemical catalytic route through

gasification would be faster, however, technical and economic viability together with requirements of material, energy and investments needs to be established to provide accurate estimate for an industrial venture.

### 21.15.8 Biothanol from waste potatoes

Ethanol fermented from renewable sources for fuel or fuel additives are known as bioethanol. Additionally, the ethanol from biomass-based waste materials is considered as bioethanol. Currently, there is a growing interest for ecologically sustainable biofuels. The target in the European Union is to increase bioenergy contributions in total energy consumption from 3 to 12 per cent by the year 2010. In Finland bioethanol is already used as additive in some gasoline products instead of toxic MTBE and TAME.

Bioethanol production from potatoes is based on the utilisation of waste potatoes. Waste potatoes are produced from 5–20 per cent of crops as by-products in potato cultivation. At present, waste potatoes are used as feedstock only in one plant in Finland. Oy Shaman Spirits Ltd. in Tyrnävä (near Oulu) uses 1.5 million kilograms of waste potatoes per year. Because this potato-based bioethanol production is just in embryo in Finland, there is a strong need for its research and development. Therefore, the aim of this study was to develop different analytical methods for bioethanol production from waste potatoes and to study the effect of potato cultivar on bioethanol production. As well, the waste solution from the distillation process was analysed.

### 21.15.9 Analytical methods for bioethanol production

In this study, methods for the determination of properties of distillates and process intermediate products in potato-based bioethanol production were tested and developed. Three methods for the determination of ethanol content were used: (i) a method based on density of sample, (ii) a method based on distillation and density measuring of sample [European Commission Regulation (EC) No 2870/2000, determination of alcoholic strength of spirit drinks] and, a method based on gas chromatography (GC).

The method tested for the analysing of volatile compounds of distillates was based on gas chromatography [European Commission Regulation (EC) No 2870/2000, determination of volatile substances and methanol of spirit drinks]. A potato hydrometer was used for the determination of starch content of potatoes.

### 21.15.10 Effect of potato cultivar on bioethanol production

Ten Swedish potato cultivars were characterised in a lab-scale bioethanol process. All potato cultivars were processed in a similar way. Experiments were performed in two phases: In the first step, we studied only cultivars numbers 1 and 2, and in the second phase the cultivars 3–10. Potatoes were processed with skin, except the cultivars 1 and 2 which had also samples without skin.

### *Lab-scale process*

Figure 21.3 presents the process for production of bioethanol from potatoes. Five kg of potatoes were used in each batch (10 kg for cultivars 1 and 2). Potato tubers were mashed to a particle size of about 5 mm. The mash was cooked in a water bath for one hour. A portion of the alpha-amylase was added before cooking. After boiling, the mash was cooled to 80–90°C and the rest of alpha amylase was added. After one-hour liquefaction, the mash was allowed to cool to 60°C for 30 minutes. Before saccharification the pH of the mash was adjusted from about 6 to 4,2-4,4 with phosphoric acid and the glucoamylase enzyme was added. After 90 minutes saccharification, the mash was cooled to 30°C and the yeast was added. During 6 days fermentation, the mash was mixed regularly. Ethanol was separated from beer with a two-phase distillation. The first distillation was in the temperature range 20–94°C. The distillate was handled with carbon and $CuSO_4$ and then the solution was distilled to a temperature of 90°C. Potato cultivars 3–7 were processed two times.

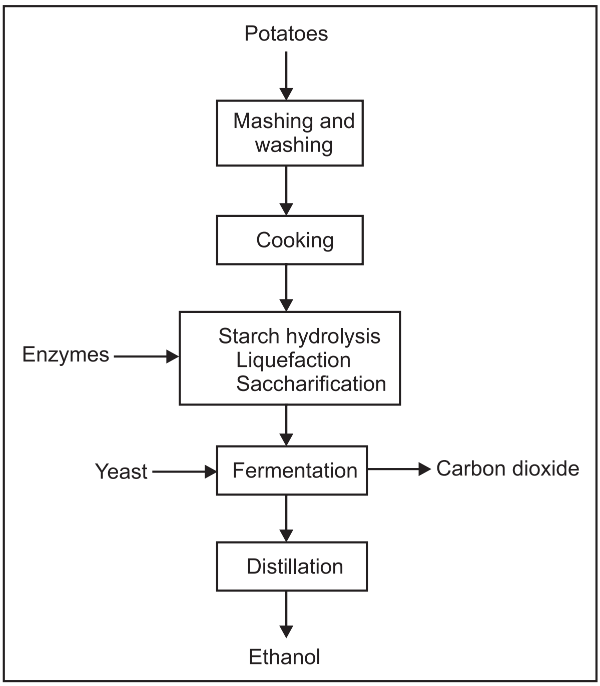



**Figure 21.3** Bioethanol production from potatoes

### *Analytical methods*

1. Dry matter contents of the potato cultivars were determined by oven-drying.
2. The starch contents of the tubers were measured with potato hydrometer.
3. The yields of alcohol were determined by distillation and measuring densities of distillates.
4. Volatile compounds of distillates were analysed with GC. The method was based on European Commission Regulation (EC) No. 2870/2000.

Properties of waste solution from distillation

Waste solutions from distillation contain quite high concentrations of impurities formed during the fermentation process. Purification of these solutions is not economically viable. However, it is possible to find other applications for these by-products, for instance in industry.

The properties analysed from waste solution of distillation during this study were alcohol content, concentrations of volatile compounds, the heat of combustion ΔHm and the heat of evaporation DvapH. Alcohol content was determined with electronic densimetry (AP Paar DMA 40). The method used for the determination of volatile compounds was based on Commission Regulation (EC) No. 2870/2000. The heat of combustion ΔHm was measured with a bomb calorimeter (Gallenkanp CB 470). The low pressure system was used to determine heat of vapourisation DvapH.

## 21.15.11 Results and discussion

### *Analytical methods for bioethanol production*

The EC method and the method based on the density of sample proved to be very accurate for the determination of alcohol content in distillates. The density method was simple and rapid, but very sensitive for the impurities of distillates. Thus, this method is best suited for pure ethanol-water systems. The EC method, which is based on distillation and determination of the density of sample, was used for distillates and intermediate products of the process. Although, precise results were achieved, the method was observed to be very sensitive for the performance of the distillation system. The method was also time-consuming. The EC method was also used for the determination of alcohol strength of the spirit beverages. Distillation of aroma compounds caused problems with some samples. However, better results were achieved when a slower distillation rate and more dilute samples were used. The method based on gas chromatography proved to be more inaccurate for the determination of alcohol content than the EC method or the density method. However, this method was rapid and practical especially for intermediate products of the process.

The method used for the determination of volatile compounds of distillates was based on gas chromatography (GC). The results indicate that this method is satisfactory for the determination of volatile components in bioethanol. Resolution for peaks was good, except for methanol and amyl alcohols (acetal was not determined). However, it was possible to analyse methanol later in lower oven temperatures. Reproducibility was also good for all components, except ethyl acetate. Linear correlation, area of the peak = f (content of the compound), was observed for all compounds. The method based on the potato hydrometer was a rapid and simple method for the determination of starch content of potatoes. This method proved to be practical for routine measurements in bioethanol plant. The precision of the results was not evaluated during this study.

## *Effect of potato cultivar on bioethanol production*

### *Effect of potato cultivar on lab-scale process*

Properties of mash varied among the potato cultivars during the hydrolysis. Potato cultivar proved to have an effect especially on dry matter content and viscosity of mash. The cultivars with high dry matter content were difficult to process. The foaming of mash also varied with potato cultivar. For three of the cultivars, the pH of mash was considerably high during liquefaction of starch. This could have influence on the activity of alpha-amylase.

### *Starch content of potatoes*

Starch contents varied from 11.2 per cent to over 19.3 per cent (Table 21.9). Potato cultivar 9 had exceptionally high starch content. This cultivar was also very difficult to process during the hydrolysis. For the other cultivars, differences were smaller. However, these small differences are significant for ethanol yield. For instance, the theoretical alcohol yield for cultivar 7 is over 25 per cent higher than for cultivar 6.

### *Dry matter content of potatoes*

Dry matter contents varied from 16.0 per cent to 27.3 per cent (Table 21.9). Potato cultivars 5 and 9 had very high dry matter content. Dry matter content of the potatoes was observed to have an effect on starch hydrolysis. Potatoes with high dry matter content were difficult to process.

### *Ethanol yield*

Alcohol yields varied significantly between cultivars (Table 21.9). The highest alcohol yield was 9.5 g/100 g (cultivar 9) and the lowest yield 6.5 g/100 g (cultivar 10). The average alcohol yield was 7.6 g/100 g. The alcohol yield of cultivar 9 was over 40 per cent greater that of the cultivar 10. Potato skin proved to have a little effect on the alcohol yield.

The yield was bigger for the potatoes, which had a skin. Alcohol yield-% was high for all cultivars except the cultivar 6. For some cultivars, the yield-% was over 100 per cent. This can be explained to be due to the evaporation of water during hydrolysis.

**Table 21.9** Properties of some potato cultivars.

| Cultivar | Dry matter content (%) | Starch content (%) | Ethanol yield (g EtOH/100 g) | Theoretical yield (g EtOH/100 g) | Yield-% (%) |
|---|---|---|---|---|---|
| 3 | 20.7 | 13.8 | 8.1 | 7.8 | 103 |
| 4 | 17.8 | 12.9 | 7.2 | 7.3 | 99 |
| 5 | 22.9 | – | 8.2 | – | – |
| 6 | 17.8 | 11.2 | 6.6 | 6.4 | 103 |
| 7 | 20.3 | 14.1 | 8.4 | 8.0 | 104 |
| 9 | 27.3 | >19.3 | 9.5 | >10.95 | <87 |
| 10 | 16.0 | – | 6.5 | – | – |

## *Volatile compounds in the distillates*

The amount of volatile compounds varied slightly in the distillates (Table 21.10). However, there was not a clear trend between cultivars. The biggest differences were between the two sample groups (cultivars 1 and 2 versus cultivars 3–10). Thus the results indicate that process conditions have a significant influence on the formation of volatile compounds. Differences in the total amount of the volatile compounds were also quite small. Differences in the replicate analysis were almost as large as that of different cultivars.

**Table 21.10** Concentrations of volatile compounds in the distillates (g/100 $dm^3$ ethanol).

| Cultivar | Methanol | 1-Propanol | 2-Methylpropanol | Amyl alcohols[a] | Ethylacetate | Asetaldehyde | Σ |
|---|---|---|---|---|---|---|---|
| 1 | 55 | 94 | 71 | 267 | 40 | 191 | 718 |
| 1b | 65 | 49 | 113 | 372 | 25 | 110 | 734 |
| 2 | 71 | 62 | 43 | 221 | 36 | 23 | 456 |
| 2b | 69 | 77 | 40 | 400 | 44 | 29 | 659 |
| 3 | 49 | 111/107 | 76/58 | 296/235 | 80/87 | 43/57 | 655/593 |
| 4 | 62 | 102/102 | 73/65 | 278/215 | 93/65 | 42/21 | 650/530 |
| 5 | 83 | 109/115 | 53/50 | 157/268 | 77/48 | 29/40 | 508/604 |
| 6 | 85 | 150/115 | 56/56 | 207/197 | 63/55 | 54/53 | 615/561 |
| 7 | 45 | 147/132 | 62/65 | 292/221 | 80/65 | 24/15 | 650/543 |
| 8 | 78 | 111 | 62 | 246 | 99 | 52 | 648 |
| 9 | 12 | 108 | 75 | 266 | 88 | 83 | 632 |
| 10 | 41 | 115 | 58 | 209 | 66 | 52 | 541 |

[a]2-Methyl-1-butanol and 3-methyl-1-butanol

[b]Potato without skin

### *Properties of the waste solution from distillation*

The results indicate that the physico-chemical properties of by-products from distillation are relatively close to absolute ethanol. The alcohol content of the by-product was high at 95 vol %. Table 21.11 presents the heat of combustion ΔHm for the by-product and reference materials. The heat of combustion for the by-product was only 15 per cent lower than for absolute ethanol. In addition, the heat of vapourisation DvapH was near to absolute ethanol. The concentrations of volatile compounds of the by-product were relatively low (total amount 1,2 mass per cent). The main component of the by-product was methanol (7 mg/g). Other compounds that were detected were ethyl acetate, 1-propanol, 2-butanol and acetaldehyde.

**Table 21.11** The heat of combustion ΔHm for a sample of by-product of potato-based bioethanol and reference materials.

| Sample | Heat of combustion DHm (kJ/g) |
|---|---|
| By-product | 31.7 |
| Etax Aa (Ethanol >99.7 vol%) | 37.1 |
| Etax B (Ethanol 94.95 vol%) | 34.2 |

## 21.16 Utilisation of alcohol in vehicular engines

Extensive experimental tests and computerised theoretical investigations carried out by various scientists have shown that ethyl alcohol can be utilised with great advantage in existing automobile/scooter/motorcycle engines, in the form of !!alcohol–gasoline blends without any major engine modifications. After extensive trials, an 'optimum' blend has been perfected which gives improved performance, lesser consumption, lesser exhaust emission, very much reduced carbon deposits, and smoother and cooler engine operation as compared to that obtained with gasoline alone. Effective additives have been developed and perfected to stabilise the 'optimum blend, denature it and give it a distinct colour and odour.

Carburation of ethyl alcohol in heavy vehicular engines powered by diesel has been found to increase their power rating by 20–50 per cent depending upon the type of combustion chamber used. Engine noise level and exhaust smoke density reduces considerably with the use of ethyl alcohol as a biofuel in these engines.

### 21.16.1 Vehicular engines and fuels

There are now more than two hundred million passenger cars, trucks and buses the world over using combustion engines. Of these the Spark Ignition engines, burning gasoline, are almost exclusively the power plants for passenger cars and light trucks. Diesel engines, using another petroleum product, diesel oil, power most of the trucks and buses. The total horsepower of these engines used in automobiles and trucks alone amounts to many times more than the entire installed horsepower of central power stations the world over. These engines continue to grow in numbers and it is hard to see a replacement for them in the foreseeable future. Their growing number has made modern industrial civilisation dependent on oil.

Both gasoline and diesel oil used in these vehicles are ‘stored’ fuels extracted from the earth. There are limited reserves of these fuel oils and economists are haunted with the knowledge that they are irreplaceable. The products of decay of prolific animal and vegetable life existing millions of years ago, the conditions that created them, no longer exist. With the present experience of expertise known resources and the present rate of consumption it is feared that they will not last long.

It is, therefore, necessary and desirable to search out and investigate the possibility of using ‘unstored’ liquid fuels which can be synthetically prepared from such renewable stores of raw materials that are available in nature in abundance.

## *Ethanol-based engines*

Ethanol is most commonly used to power automobiles, though it may be used to power other vehicles, such as farm tractors and airplanes. Ethanol (E100) consumption in an engine is approximately 51 per cent higher than for gasoline since the energy per unit volume of ethanol is 34 per cent lower than for gasoline. However, the higher compression ratios in an ethanol-only engine allow for increased power output and better fuel economy than could be obtained with lower compression ratios. In general, ethanol-only engines are tuned to give slightly better power and torque output than gasoline-powered engines. In flexible fuel vehicles, the lower compression ratio requires tunings that give the same output when using either gasoline or hydrated ethanol. For maximum use of ethanol’s benefits, a much higher compression ratio should be used, which would render that engine unsuitable for gasoline use. When ethanol fuel availability allows high-compression ethanol-only vehicles to be practical, the fuel efficiency of such engines should be equal or greater than current gasoline engines. The mileage (miles-per-gallon) is therefore usually 20–30 per cent higher than a gasoline-only engine.

A 2004 MIT study and an earlier paper published by the society of automotive engineers identify a method to exploit the characteristics of fuel ethanol substantially better than mixing it with gasoline. The method presents the possibility of leveraging the use of alcohol to achieve definite improvement over the cost-effectiveness of hybrid electric. The improvement consists of using dual-fuel direct-injection of pure alcohol (or the azeotrope or E85) and gasoline, in any ratio up to 100 per cent of either, in a turbocharged, high compression-ratio, small-displacement engine having performance similar to an engine having twice the displacement. Each fuel is carried separately, with a much smaller tank for alcohol. The high-compression (which increases efficiency) engine will run on ordinary gasoline under low-power cruise conditions. Alcohol is directly injected into the cylinders (and the gasoline injection simultaneously reduced) only when necessary to suppress 'knock' such as when significantly accelerating. Direct cylinder injection raises the already high octane rating of ethanol up to an effective 130. The calculated over-all reduction of gasoline use and $CO_2$ emission is 30 per cent. The consumer cost payback time shows a 4:1 improvement over turbo-diesel and a 5:1 improvement over hybrid. In addition, the problems of water absorption into pre-mixed gasoline (causing phase separation), supply issues of multiple mix ratios and cold-weather starting are avoided.

Ethanol's higher octane rating allows an increase of an engine's compression ratio for increased thermal efficiency. In one study, complex engine controls and increased exhaust gas recirculation allowed a compression ratio of 19.5 with fuels ranging from neat ethanol to E50. Thermal efficiency up to approximately that for a diesel was achieved. This would result in the MPG (miles per gallon) of a dedicated ethanol vehicle to be about the same as one burning gasoline.

Since 1989 there have also been ethanol engines based on the diesel principle operating in Sweden. They are used primarily in city buses, but also in distribution trucks, and waste collectors use this technology. The engines, made by Scania, have a modified compression ratio, and the fuel (known as ED95) used is a mix of 93.6 per cent ethanol and 3.6 per cent ignition improver, and 2.8 per cent denaturants. The ignition improver makes it possible for the fuel to ignite in the diesel combustion cycle. It is then also possible to use the energy efficiency of the diesel principle with ethanol.

## *Engine cold start during the winter*

High ethanol blends present a problem to achieve enough vapour pressure for the fuel to evaporate and spark the ignition during cold weather (since ethanol tends to increase fuel enthalpy of vapourisation). When vapour pressure is below 45 kPa starting a cold engine becomes difficult. In order to avoid this problem at temperatures below 11°C (59°F), and to reduce ethanol higher emissions during cold weather, both the US and the European markets adopted

E85 as the maximum blend to be used in their flexible fuel vehicles, and they are optimised to run at such a blend. At places with harsh cold weather, the ethanol blend in the US has a seasonal reduction to E70 for these very cold regions, though it is still sold as E85. At places where temperatures fall below –12°C (10°F) during the winter, it is recommended to install an engine heater system, both for gasoline and E85 vehicles. Sweden has a similar seasonal reduction, but the ethanol content in the blend is reduced to E75 during the winter months.

Brazilian flex fuel vehicles can operate with ethanol mixtures up to E100, which is hydrous ethanol (alcohol with up to 4 per cent water), which causes vapour pressure to drop faster as compared to E85 vehicles, and as a result, Brazilian flex vehicles are built with a small secondary gasoline reservoir located near the engine to avoid starting problems in cold weather. The cold start with pure gasoline is particularly necessary for users of Brazil's southern and central regions, where temperatures normally drop below 15°C (59°F) during the winter. An improved flex motor generation that will be launched shortly which will eliminate the need for this secondary gas storage tank.

## *Ethanol fuel mixtures*

To avoid engine stall due to 'slugs' of water in the fuel lines interrupting fuel flow, the fuel must exist as a single phase. The fraction of water that an ethanol-gasoline fuel can contain without phase separation increases with the percentage of ethanol. This shows, for example, that E30 can have up to about 2 per cent water. If there is more than about 71 per cent ethanol, the remainder can be any proportion of water or gasoline and phase separation will not occur. However, the fuel mileage declines with increased water content. The increased solubility of water with higher ethanol content permits E30 and hydrated ethanol to be put in the same tank since any combination of them always results in a single phase. Somewhat less water is tolerated at lower temperatures. For E10 it is about 0.5 per cent v/v at 70°F and decreases to about 0.23 per cent v/v at –30°F.

In many countries cars are mandated to run on mixtures of ethanol. Brazil requires cars be suitable for a 25 per cent ethanol blend, and has required various mixtures between 22 and 25 per cent ethanol. The United States allows up to 10 per cent blends, and some states require this (or a smaller amount) in all gasoline sold. Other countries have adopted their own requirements. Beginning with the model year 1999, an increasing number of vehicles in the world are manufactured with engines which can run on any fuel from 0 per cent ethanol up to 100 per cent ethanol without modification. Many cars and light trucks (a class containing minivans, SUVs and pickup trucks) are designed to be flexible-fuel vehicles (also called dual-fuel vehicles).

In older model years, their engine systems contained alcohol sensors in the fuel and/or oxygen sensors in the exhaust that provide input to the engine control computer to adjust the fuel injection to achieve stochiometric (no residual fuel or free oxygen in the exhaust) air-to-fuel ratio for any fuel mix. In newer models, the alcohol sensors have been removed, with the computer using only oxygen and airflow sensor feedback to estimate alcohol content. The engine control computer can also adjust (advance) the ignition timing to achieve a higher output without pre-ignition when it predicts that higher alcohol percentages are present in the fuel being burned. This method is backed up by advanced knock sensors—used in most high performance gasoline engines regardless of whether they are designed to use ethanol or not—that detect preignition and detonation.

## *Fuel economy*

In theory, all fuel-driven vehicles have a fuel economy (measured as miles per US gallon, or litres per 100 km) that is directly proportional to the fuel's energy content. In reality, there are many other variables that come into play that affect the performance of a particular fuel in a particular engine. Ethanol contains approximately 34 per cent less energy per unit volume than gasoline, and therefore in theory, burning pure ethanol in a vehicle will result in a 34 per cent reduction in miles per US gallon, given the same fuel economy, compared to burning pure gasoline. This assumes that the octane ratings of the fuels, and thus the engine's ability to extract energy from the fuels, are the same. For E10 (10 per cent ethanol and 90 per cent gasoline), the effect is small (~3 per cent) when compared to conventional gasoline, and even smaller (1–2 per cent) when compared to oxygenated and reformulated blends. However, for E85 (85 per cent ethanol), the effect becomes significant. E85 will produce lower mileage than gasoline, and will require more frequent refueling. Actual performance may vary depending on the vehicle. Based on EPA tests for all 2006 E85 models, the average fuel economy for E85 vehicles resulted 25.56 per cent lower than unleaded gasoline. The EPA-rated mileage of current USA flex-fuel vehicles should be considered when making price comparisons, but it must be noted that E85 is a high performance fuel, with an octane rating of about 104, and should be compared to premium. In one estimate the US retail price for E85 ethanol is 2.62 US dollar per gallon or 3.71 dollar corrected for energy equivalency compared to a gallon of gasoline priced at 3.03 dollar. Brazilian cane ethanol (100 per cent) is priced at 3.88 dollar against 4.91 dollar for E25 (as July 2007).

## *Alcohol: The renewable fuel*

Ethyl alcohol, commonly called alcohol and technically termed ethanol, is one such fuel. Its importance lies in the ease with which it can be prepared from an astonishingly wide range of raw materials, some of which are to be found in every habitable country on the globe. These raw materials include vegetable matter, growing crops, farm waste, tropical grasses, waste organic products such as straw and saw dust, molasses, water gas, industrial wastes like sulphite liquor from the paper and pulp industry, and many others.

Its use may be regarded as a direct method of obtaining energy from the sun without the intermediary of storage in earth for a long period of time. As long as the sun shines, plants will perform their synthesis of starch from the abundant carbon dioxide and water that bathe our planet. From this annually-renewed store of raw materials, ethanol can be readily produced in quantities sufficient to meet the world demand. It thus has attributes of perennial renewal.

## *Alcohol as automobile fuel*

Ethanol, if used as an automobile engine fuel, offers certain advantages. The chief amongst them is the possibility of high compression operation without knock. It is an anti-knock fuel and has the ability to stand very high compression ratios. Its octane rating is above 100 and it could operate safely at compression ratios around 12. It has a high latent heat of vapourisation. This property can be utilised to achieve lower charge temperature during induction, higher charge density; hence higher volumetric efficiency and cooler engine operation.

The absence of pre-ignition and knock resistance makes it suitable for high-output engines and opens the option of supercharging of the engine, which is seriously restricted with gasoline fuel.

Ethanol is also safer than gasoline due to its higher flash point. Its vapours are not quite half as heavy as those of gasoline, so that it does not flow and accumulate in dangerous quantities at low levels; and a higher proportion is needed to form an explosive mixture with air. Hence the fuel tank is less likely to catch fire in case of accident. Its uniformity of composition and much cleaner combustion are some other advantages. It tends to produce less carbon deposits than normal gasoline and the deposits are softer and easier to remove. Its lower calorific value, higher viscosity, greater surface tension and hygroscopic nature are some of the difficulties in its use as a complete fuel in the present-day combustion engines. It can however be mixed with other fuel or fuel mixtures so as to impart to the resulting blend some of its important properties, namely higher compression operation without knock, cleaner combustion and cooler engine operation.

### *Alcohol and vehicular emissions*

There is another aspect of automative engine operation. Its exhaust contains atmospheric pollutants like carbon monoxide, carbon dioxide, unburned hydrocarbons, oxides of nitrogen, lead salts, soot, aldehydes, ketones, etc. An automobile discharges around 0.66 tons of carbon monoxide over a period of a year and it is estimated that automobile exhaust is the source of ninety per cent of carbon monoxide found in the atmosphere of the USA. Oxides of nitrogen and unburned hydrocarbons from automobile exhaust create air pollution problems by forming photochemical smog. Their interaction involves formation of certain formaldehydes, peroxides, peroxyacyl nitrate, etc. which cause eye irritation, plant damage, and contribute to poor visibility.

Present day gasoline contains lead, added to raise its octane number. 98.8 per cent gasoline sold in the world market today contains tetraethyl lead. This lead ultimately finds its way, in the form of lead salts, in the exhaust effluent discharged through the tail-pipe of the vehicles; and causes lead poisoning of the environment. It is estimated that a few thousand tons of organic lead are spewed out of auto-exhausts every year.

Thus, pollutants like carbon monoxide, oxides of nitrogen, unburned hydrocarbons and lead salts from vehicular exhausts are posing a very serious health hazard. The concentration of these pollutants in the automobile exhaust effluent depends, apart from other things, on the nature of the fuel. Ethanol and its blends, unlike gasoline, provide ‘clean burning fuels’.

Their use is likely to reduce the air pollution caused by automobile exhaust emissions. With its inherently high octane rating ethanol can be used as a blending agent to raise the octane rating of gasoline and eliminate thereby the need of lead additives. Its use as automobile fuel can thus eliminate the hazard of exhaust lead poisoning of the environment.

## 21.16.3 Alcohol utilisation in light vehicular engines

Experimental and theoretical investigations have been carried out to assess the effects of ethanol blending on the performance and exhaust emission characteristics of spark ignition engines of various types, such as E6/T Ricardo Variable Compression Engine, CFR Engine, EMC four-cylinder engine. Extensive laboratory experiments have been followed by field trials using automobiles of a popular make. During these investigations, ethanol-gasoline blends, with ethanol content varying from 0 to 100 per cent, have been tried in various engines in the laboratory and in the field. Engine operation with various blends has been studied with and without engine modifications. In addition to engine performance, we have also looked into the consumption characteristics, smoothness of operation, exhaust emissions and various other aspects such as engine component compatibility with various ethanol-gasoline blends.

Apart from these aspects of engine performance and compatibility, Smith and others have also examined the problems of stabilisation of blend against separation due to absorption of moisture, denaturing the blend to prevent misuse of its alcohol content, cold starting and engine response with various ethanol-gasoline blends. In the following sections are briefly summarised some of the major inferences drawn on the basis of these studies.

### *Knock resistance*

Ethanol-gasoline blends permit a higher compression operation without knock. The ‘optimum’ compression ratio increases with the increase of ethanol percentage in the blend. Thus, for example, a 30 per cent ethanol-gasoline blend can operate effectively at a compression ratio about 23 per cent higher than the optimum compression ratio for gasoline. This shows that ethanol is a very effective knock suppressor, like TEL is, and has the additional advantage that it is a fuel in itself. Figure 21.4 shows the effect of adding ethanol to a typical regular gasoline with a research Octane number of 91.0. Addition of ethanol up to 10 per cent raises the octane rating of gasoline by 3 while blending 25 per cent ethanol raises the octane number of gasoline from 91 to 99.

The octane number appears to increase linearly with the increase of ethanol content in the blend up to 25 per cent ethanol addition. It has also been observed that this useful effect of ethanol blending is more marked if the starting stock is low grade gasoline, while improvement in octane rating is relatively less in case of high-octane gasoline. The high knock resistance of ethanol can be utilised in three ways: (i) as a blend constituent for improving straight-run or other spirit of low octane number, (ii) as a complete fuel in special ‘ethanol’ engines of higher compression ratio of the order of 12 or so, and (iii) as a dual-fuel for separate injection when required. The ordinary motor engine makes full use of the high knock rating of the fuel only during a small portion of its service. If it were operated on a cheaper fuel of relatively low rating but with automatic means of ethanol injection under high loads the biofuel combination might make for greater economy.

### *Optimum blend*

From intensive tests carried out on unmodified engines, the ‘optimum’ blend has been found. This blend gives improved engine performance, less exhaust emissions and smoother operation of the engine as compared to gasoline. This blend can be utilised in existing automobiles without any major modifications.

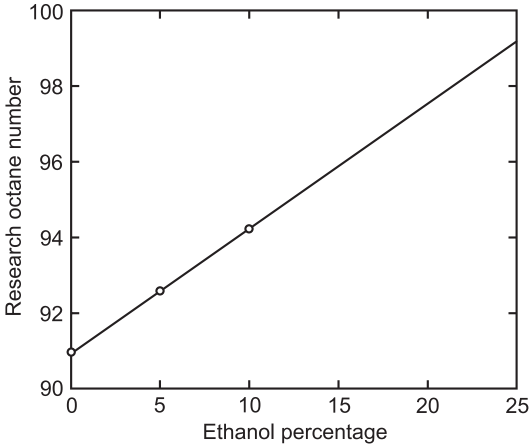



**Figure 21.4** Variation of octane rating with the ethanol percentage in the blend

## *Water tolerance of the blend*

The ‘optimum’ blend has been stabilised against separation due to absorption of moisture by providing some additives. ‘Water tolerance’ at various temperatures has been determined and often found within the prescribed limits set by the Indian power alcohol rules. The ‘optimum’ blend does not show any turbidity or any other sign of separation when cooled even below 0°C. During the course of many years of the use of this blend in the laboratory and in the field, not a single case of separation has come to light.

## *Denaturing of the blend*

The blend has been denatured to prevent illegal diversion of ethanol. Various denaturing agents were considered and tried in laboratories. The one finally selected satisfies most of the requirements of the denaturants. This, when used in very small quantities, effectively denatures the blend, gives a pungent smell and burning taste. No trouble has been found with this denaturing agent so far. Engine wear and deposits with the blend

After 200 hours run using the blend, the wear of engine components was in no way more than that with gasoline while the ‘optimum’ blend showed carbon deposit which was about 115 of the carbon deposits obtained with gasoline.

## *Corrosion with the blend*

The prolonged use of the blend may at times cause corrosion of surface components due to the production of acid bodies. The silencer has been found to suffer most. In some experiments, this problem was overcome by neutralising the acid products which cause corrosion by using small amounts of additives.

Copper and iron, as also rubber gaskets, are susceptible to attack by ethanol. However, this problem is encountered only when the percentage of ethanol in the blend is very high. Suitable measures such as ‘tinning’ can prevent this problem vis-à-vis the fuel tank. With the small percentage of ethanol in the ‘optimum’ blend recommended, this problem is not serious. As a matter of fact, this type of problem does occur even with the use of leaded gasoline. For example, the use of gasoline tends to build up deposits on spark plugs and attack the mica or porcelain. None of these difficulties can arise with the use of the ethanol blend. In some experiments it was observed that the temperature of the spark plugs is reduced with the ‘optimum’ blend and this has the effect of prolonging their life.

### *Ease of starting with the blend*

No greater difficulty than that experienced with gasoline has been encountered in starting up the engine with the ‘optimum’ blend. In fact, the startability of the engine improves with ethanol addition up to a maximum of about 20 per cent of ethanol. Even at 0°C the addition of a small amount of ethanol (as recommended for ‘optimum’ blend) improves the startability of the engine. At 10°C, somewhat similar results are obtained except that the difference in starting time with ‘optimum’ blend and gasoline becomes less marked.

### *Vapour lock and the blend*

Increase of the vapour pressure of the ethanol-gasoline blend (having low ethanol content) with temperature is not significantly different from that of gasoline and consequently blends containing a small percentage of ethanol (as recommended for the ‘optimum’ blend) should not be more susceptible to vapour lock than gasoline. Experiments have shown that the ‘ten per cent’ point on the distillation curve is at more or less the same temperature for the ‘optimum’ blend as for gasoline.

### *Engine warm-up with the blend*

The ‘warming up’ of the engine from start appears to be slower and greater acceleration has to be given just after the start to encourage rapid warming up. This characteristic of the blend should not be considered a disadvantage. In fact, when starting from cold it is not advisable to accelerate the engine to top speed and power in the shortest possible time.

### *Power and consumption with the blend*

During the road tests it has been noted that power as also fuel consumption is not affected while using the 'optimum' blend. Slight adjustment in ignition timing is necessary to ensure the complete combustion to the blended fuel. With proper adjustments made in the ignition system, generally the same mileage was recorded as for gasoline, although theoretically the blend has slightly lower calorific value. This may be possible due to better combustion characteristics of the blend.

### *Alcohol blends and engine performance*

Blends having more than 25 per cent of ethanol have no advantage over gasoline when used in the engine without modifications; hence they are of little practical value so far as the present-day vehicular engines are concerned. At 'optimum' conditions for each blend, the gain in power output is very marked. With 30 per cent blend the maximum BHP is about 11 per cent more than that with gasoline. Thus, by taking advantage of increase in ignition advance with ethanol blends and using higher compression ratios made available by the antiknock nature of ethanol, marked improvement in the power output can be achieved. Figure 21.5 shows that at any given compression ratio the engine brake mean effective pressure (indicative of engine power output) increases as the 'ethanol content increases' from 0 to 30 per cent. The increase in power output that is obtained as the compression ratio of the engine is increased is also apparent. When the compression ratio reaches 9:1 the octane number of the regular grades of fuel is insufficient to prevent knocking. Hence the power falls off rapidly in this area of knock with ethanol concentrations of less than about twenty per cent.

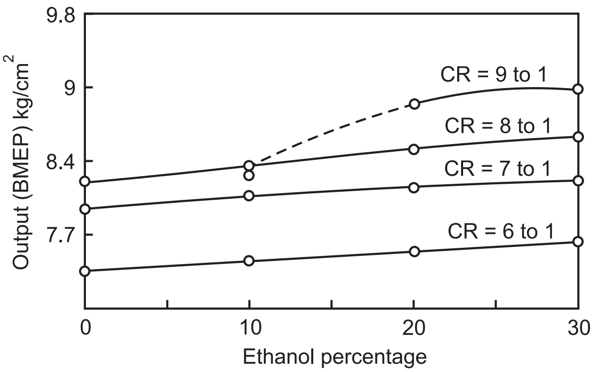



**Figure 21.5** Variation of engine power output with ethanol percentage in the blend at various compression ratios

Figure 21.6 shows the effect of ethanol concentration on the specific fuel consumption of the engine. There is a clear improvement in fuel consumption associated with increasing the compression ratio of the engine made possible by ethanol blending. It may be observed from the figure that the fuel consumption is initially reduced as ethanol concentration is raised to a level of 10–20 per cent. At compression ratio 9:1 the detrimental effect of knock is again apparent as indicated by the curve at ethanol concentrations of less than about 20 per cent.

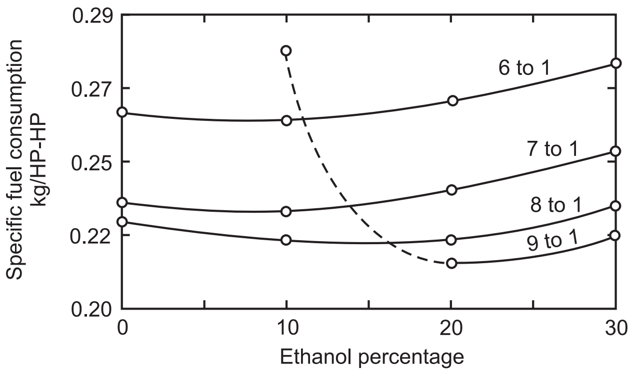



**Fig. 21.6.** Variation of specific fuel consumption with ethanol percentage in the blend at various compression ratios.

## *Alcohol blends and exhaust emissions*

A change to ethanol blends without modifications or adjustment results in less carbon monoxide in the exhaust effluent than with gasoline as a fuel. This provides a simple way of reducing or completely eliminating carbon monoxide from the engine exhaust by the mere addition of ethanol to gasoline. Thus ethanol addition up to about 20 per cent removes even traces of carbon monoxide in exhaust gas, at the best power ratio for gasoline, when under similar conditions, operation with gasoline would result in about 3 per cent carbon monoxide in the exhaust effluent. Figure 21.7 shows the exhaust CO and NOx concentrations computed for various ethanol-gasoline blends of practical utility, using a special computer program, HBMR, developed by Smith. The theoretically predicted results confirm the conclusions drawn from the experimental results.

The addition of ethanol reduces unburned hydrocarbons in the exhaust effluent of an unmodified gasoline engine by a substantial amount. Thus, the addition of ethanol up to 15 per cent or so reduces exhaust hydrocarbon concentrations up to 30 per cent depending on the air-fuel ratio. Figure

21.8 summarizes the effect of ethanol blending on exhaust hydrocarbon concentrations determined experimentally using gas-chromatographic analysis technique. A typical gas chromatogram obtained during the test is shown in Fig. 21.9.

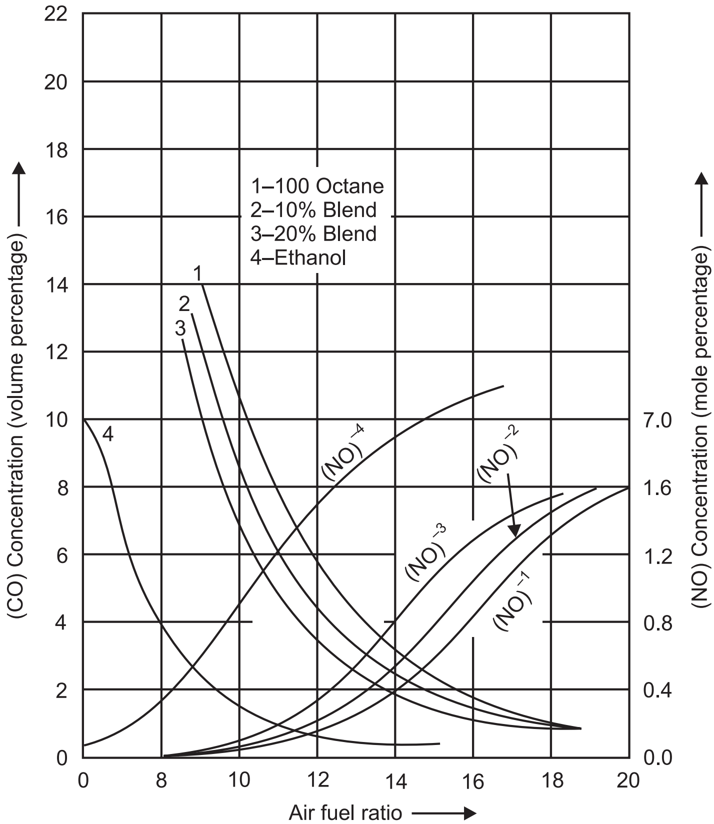



**Figure 21.7** Calculated (NO) concentration and (CO) percentage vs. air fuel ratios for various fuels

## *Ethanol/alcohol engine*

Neat ethanol can be utilised as a complete fuel in 'ethanol engines' specially designed for this purpose. Such engines would have a high compression ratio of the order of 12 or so, a high-energy ignition source such as a magneto, and a carburettor specially designed for ethanol with larger jet sizes. Computerised design data have been obtained and designs have been prepared for the major components of an 'ethanol engine' by the Smith for future use. Computerised predictions show that such an engine would give much more specific output and around 10–15 per cent higher thermal efficiency.

Although an existing automobile can be modified to demonstrate its operation with ethanol neat, its reliability and life would be seriously jeopardized unless all the major components such as crank shaft, piston, connecting rods, etc. are replaced with much stronger units to withstand the higher peak pressure associated with the increase of compression ratio, every one unit increase of which causes peak cycle pressure to increase by about 120 psi.

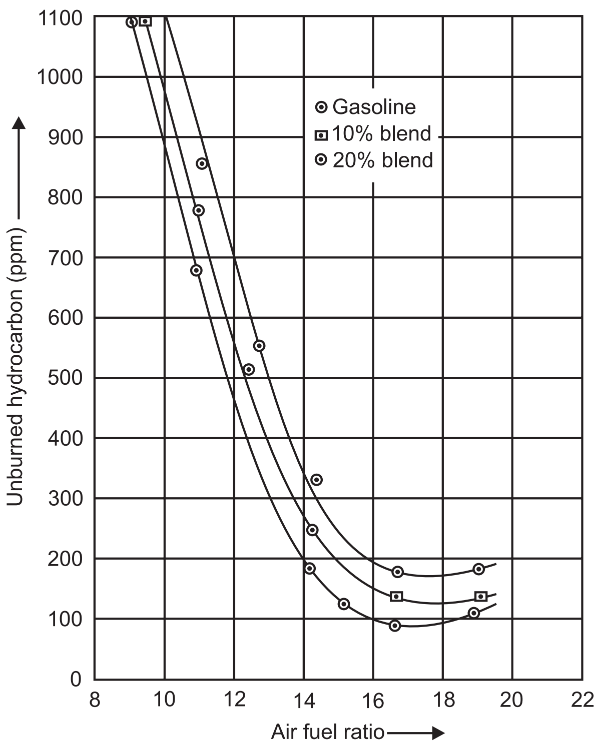



**Figure 21.8** Unburned hydrocarbon concentration in engine exhaust vs. air–fuel ratio

In summary, ethanol offers some interesting advantages as a motor fuel. Modern high-compression spark ignition engines used for automobiles/motor cycles/scooters and light trucks can, apparently, make good use of ethanol-gasoline blends without modifications and offer, at the same time, reduced carbon monoxide and unburnt hydrocarbon in the exhaust effluent. Ethanol blending thus provides a partial but immediate solution to the twin problems of fuel scarcity and growing automobile exhaust pollution.

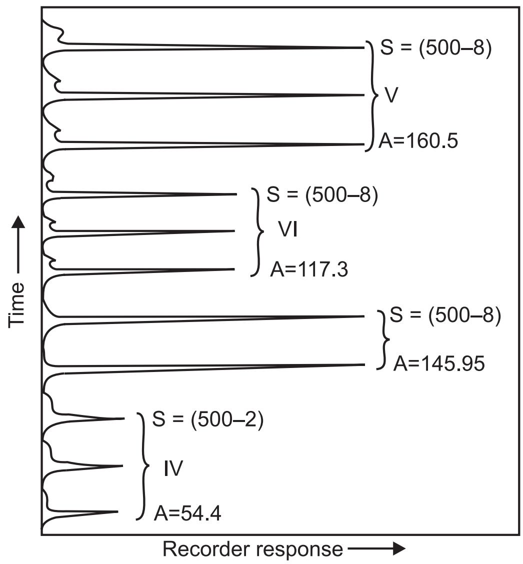



**Figure 21.9** Chromatograms showing unburned hydrocarbon concentration at various air–fuel ratios. Fuel 10 per cent ethanol–gasoline blend

## 21.16.4 Alcohol utilisation in heavy vehicular engines

Experimental studies so far completed under an ongoing program entitled Project U: 'Utilisation of unconventional alternative fuels for national energy needs' currently in progress at the department of mechanical engineering and centre of energy studies at IIT, Delhi, have shown that the use of ethanol in heavy vehicles powered by compression ignition engines is beneficial, since it reduces the vehicular exhaust smoke density, increases the overload capacity of the engine and improves the thermal efficiency as well as the air utilisation factor. Best results are obtained with direct injection engines. By inducting ethanol so as to have biofuel operation of the engine, engine deposits are reduced and there is no increase of wear of the engine components. By the judicious application of mixture heating, normal thermal efficiency can be maintained at part loads and it can be surpassed at full load and overload conditions. Figures 21.10 and 21.11 show the typical test results obtained from a four-cylinder direct injection automotive diesel engine having ethanol induction. Ethanol was carburetted and tests were conducted to cover the entire load-speed range. It can be seen from Fig. 21.10 that the percentage of ethanol inducted at full load is sensibly the same over most of the speed range. Figure 21.11 shows that above half-load operation, the thermal efficiency is not adversely affected by induction of ethanol over the working speed range.

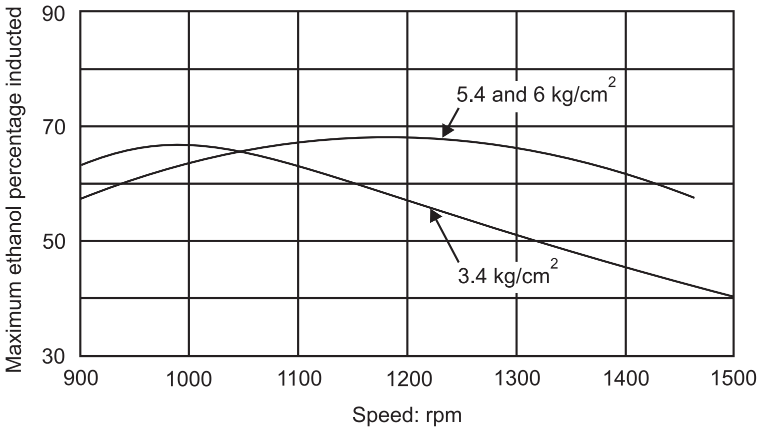



**Figure 21.10** Variation of maximum ethanol percentage inducted at various speeds

It was observed during the tests that the overload capacity of the engine as well as its thermal efficiency increased appreciably with ethanol induction. In one case thermal efficiency as high as 43 per cent was obtained under overload conditions. However, it was noted that the part-load performance of the engine deteriorated with ethanol induction.

The presence of ethanol in the inducted charge increases the delay period considerably at part-load, impairing the combustion process and hence engine performance. This malady can be overcome by the addition of heat to the air-ethanol mixture before admission to the engine. Heating of the inducted mixture to the optimum value restores the delay period almost to the normal value. By judicious application of mixture heating on lines similar to that in SI engines, the normal thermal efficiency can be maintained at part loads and surpassed at full and overload conditions as shown in Fig. 21.12 which is based on results obtained in test trials carried out with induction heating.

Detailed studies and extensive tests on alcohol-based fuels, carried out by various scientists in the last 20 years or so, have convincingly shown that in ethanol we have a fuel which, despite its drawbacks, can provide a low knock fuel with power to stand high compression ratios. Capable of being produced in any country that can support growing crops or with access to by-products of tropical zones, it enables countries with no indigenous oil deposits to provide a satisfactory motor spirit at minimum cost.

Its use in present-day automobiles in the form of ethanol-gasoline blends can be an immediate short-term measure which can stretch the available fuel supplies and help meet the energy crisis. As a long-term solution to the present-day fuel oil scarcity, vehicular engines can be designed to accommodate ethanol heat as fuel. Carburation of ethanol in heavy vehicles powered by diesel engines can increase their power ratings by 20–50 per cent depending upon the type of combustion chamber. This has an added attraction for road transport engines in that it reduces the noise level and exhaust smoke density. Ethanol/ethyl alcohol can thus go a long way to provide a solution to the twin problems of fuel oil scarcity and growing air pollution due to vehicular engine exhaust emission.

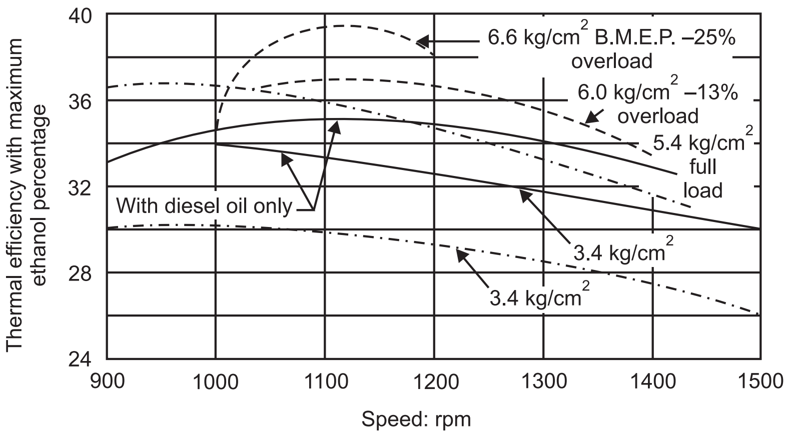



**Figure 21.11** Performance of a four-cylinder direct injection engine with ethanol induction

## 21.17 Conclusion

1. Though it is technically feasible to design and run automobiles on 100 per cent ethanol, for the reason of availability and compatibility with vehicles presently in use blending of ethanol with motor spirit needs to make a very modest beginning.
2. Five per cent blending has already been introduced in some states. According to the information availability about production and demand of ethanol for all applications, production of molasses and distillery capacity, 7 per cent blend of ethanol in gasoline is feasible provided facilities to dehydrate alcohol are added to the required extent.
3. Ethanol may be manufactured using molasses as the raw material. If the industry finds it economically feasible, it should be encouraged to produce alcohol also from sugarcane juice directly in areas where sugarcane is surplus.

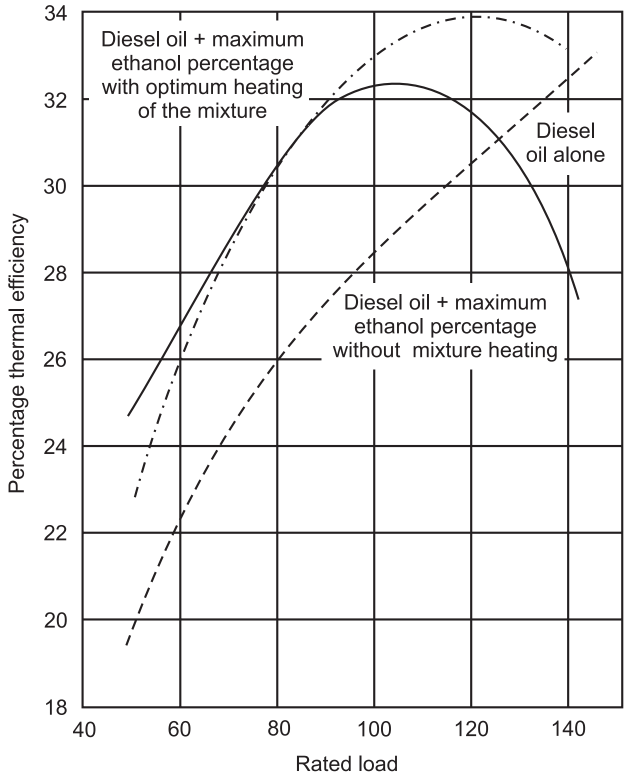



**Figure 21.12** Effect of mixture heating (with induction of maximum quantity of ethanol) on engine performance

4. Restrictions on movement of molasses and putting up ethanol manufacturing plants may be removed.
5. Imported ethanol should be subject to suitable duties so that domestically produced ethanol is not costlier than the imported one.
6. Ethanol diesel blending requires emulsifier and also poses certain storage and technical problems. Indian Institute of Petroleum is working on the subject. Ethanol diesel blending should await the solution of the problems.
7. Buyback arrangement with oil companies for the uptake of anhydrous alcohol should be made.
8. To reduce cost of production of ethanol, the following measures may be considered:

(a) Provision of incentives for new economic sized distilleries incorporating state of art technology such as, molecular sieve technology for making anhydrous alcohol.
(b) Integration of distillery with sugar plant to have multiple choice of making sugar or direct sugarcane to ethanol.

9. The cost of ethanol produced using other raw materials such as grains, potato, sugar beet and straw is estimated to be more than the price of motor spirit and may need subsidy. Economics of ethanol production from other feedstocks as sugar beet, corn, potatoes, etc. should be studied. It may be left to the industry to use these raw materials for producing ethanol as and when if it finds them economical.
10. R&D may be supported to reduce the cost of ethanol production from different feed stocks.

# 22
# Biodiesel

## 22.1 Introduction

Biodiesel refers to a vegetable oil- or animal fat-based diesel fuel consisting of long-chain alkyl (methyl, propyl or ethyl) esters. Biodiesel is typically made by chemically reacting lipids [e.g. vegetable oil, animal fat (tallow)] with an alcohol. Biodiesel is meant to be used in standard diesel engines and is thus distinct from the vegetable and waste oils used to fuel converted diesel engines. Biodiesel can be used alone or blended with petrodiesel. Biodiesel can also be used as a low carbon alternative to heating oil.

Biodiesel is fatty acid ethyl or methyl ester made from virgin or used vegetable oils (both edible and nonedible) and animal fats. The main commodity sources for biodiesel in India can be nonedible oils obtained from plant species such as *Jatropha curcas (Ratanjyot), Pongamia pinnata (Karanj), Calophyllum inophyllum (Nagchampa),* Hevca brasiliensis (Rubber), etc. Biodiesel contains no petroleum, but it can be blended at any level with petroleum diesel to create a biodiesel blend or can be used in its pure form. Just like petroleum diesel, biodiesel operates in compression ignition engine; which essentially require very little or no engine modifications because biodiesel has properties similar to petroleum diesel fuels. It can be stored just like the petroleum diesel fuel and hence does not require separate infrastructure.

The use of biodiesel in conventional diesel engines results in substantial reduction of unburnt hydrocarbons, carbon monoxide and particulate matters. Biodiesel is considered clean fuel since it has almost no sulphur, no aromatics and has about 10 per cent built-in oxygen, which helps it to burn fully. Its higher cetane number improves the ignition quality even when blended in the petroleum diesel.

Biodiesel is biodegradable—up to 4 times faster than petroleum diesel—and nontoxic. It will not spontaneously ignite under normal circumstances since it has a high flash point. It has a mild, rather pleasant odour.

## 22.2 Feasibility of producing biodiesel as diesel substitute

While the country is short of petroleum reserve, it has large arable land as well as good climatic conditions (tropical) with adequate rainfall in large parts of the area to account for large biomass production each year. For the reason of edible oil demand being higher than its domestic production, there is no possibility of diverting this oil for production of biodiesel. Fortunately there is a large junk of degraded forest land and un-utilised public land, field boundaries and fallow lands of farmers where nonedible oilseeds can be grown. There are many tree species which bear seeds rich in oil. Of these some promising tree species have been evaluated and it has been found that there are a number of them such as *Jatropha curcas and Pongamia pinnata* (Honge or Karanja) which would be very suitable in our conditions. However, Jatropha curcas has been found most suitable for the purpose. It will use lands which are largely unproductive for the time being and are located in poverty-stricken areas and in degraded forests. It will also be planted on farmers' field boundaries and fallow lands. They will also be planted in public lands such as along the railways, roads and irrigation canals.

## 22.3 Production of biodiesel

Biodiesel production is the act of producing the biofuel, biodiesel, through either transesterification or alcoholysis. The process involves reacting vegetable oils or animal fats catalytically with a short-chain of aliphatic alcohols (typically methanol or ethanol).

### 22.3.1 Steps in the process

The major steps required to synthesise biodiesel are as follows.

#### *Feedstock pretreatment*

If waste vegetable oil (WVO) is used, it is filtered to remove dirt, charred food, and other non-oil material often found. Water is removed because its presence causes the triglycerides to hydrolyse, giving salts of the fatty acids (soaps) instead of undergoing transesterification to give biodiesel.

#### *Determination and treatment of free fatty acids*

A sample of the cleaned feedstock oil is titrated with a standardised base solution in order to determine the concentration of free fatty acids (carboxylic acids) present in the waste vegetable oil sample. These acids are then either esterified into biodiesel, esterified into bound glycerides or removed, typically through neutralisation.

While adding the base, a slight excess is factored in to provide the catalyst for the transesterification. The calculated quantity of base (usually sodium hydroxide) is added slowly to the alcohol and it is stirred until it dissolves. Sufficient alcohol is added to make up three full equivalents of the triglyceride, and an excess of usually six parts alcohol to one part triglyceride is added to drive the reaction to completion.

### *Product purification*

Products of the reaction include not only biodiesel, but also by-products, soap, glycerine, excess alcohol, and trace amounts of water. All of these by-products must be removed, though the order of removal is process-dependent. The density of glycerine is greater than that of biodiesel, and this property difference is exploited to separate the bulk of the glycerine by-product. Residual methanol is typically removed through distillation and reused, though it can be washed out (with water) as a waste as well. Soaps can be removed or converted into acids. Any residual water must be removed from the fuel.

## 22.3.2 Derivatives of triglycerides (vegetable oils) as diesel fuels

The alternative diesel fuels must be technically and environmentally acceptable, and economically competitive. From the viewpoint of these requirements, triglycerides (vegetable oils/animal fats) and their derivatives may be considered as viable alternatives for diesel fuels. The problems with substituting triglycerides for diesel fuels are mostly associated with their high viscosities, low volatilities and polyunsaturated character. The problems have been mitigated by developing vegetable oil derivatives that approximate the properties and performance and make them compatible with the hydrocarbon-based diesel fuels through:

1. Pyrolysis
2. Microemulsification
3. Dilution
4. Transesterification

### *Pyrolysis*

Pyrolysis refers to a chemical change caused by the application of thermal energy in the absence of air or nitrogen. The liquid fractions of the thermally decomposed vegetable oil are likely to approach diesel fuels. The pyrolysate had lower viscosity, flash point, and pour point than diesel fuel and equivalent calorific values.

The cetane number of the pyrolysate was lower. The pyrolysed vegetable oils contain acceptable amounts of sulphur, water and sediment and give acceptable copper corrosion values but unacceptable ash, carbon residue and pour point.

## *Microemulsification*

The formation of microemulsions (co-solvency) is one of the potential solutions for solving the problem of vegetable oil viscosity. Microemulsions are defined as transparent, thermodynamically stable colloidal dispersions. The droplet diameters in microemulsions range from 100 Å to 1000 Å. A microemulsion can be made of vegetable oils with an ester and dispersant (co-solvent) or of vegetable oils, an alcohol and a surfactant and a cetane improver, with or without diesel fuels. Water (from aqueous ethanol) may also be present in order to use lower-proof ethanol, thus increasing water tolerance of the microemulsions.

## Dilution

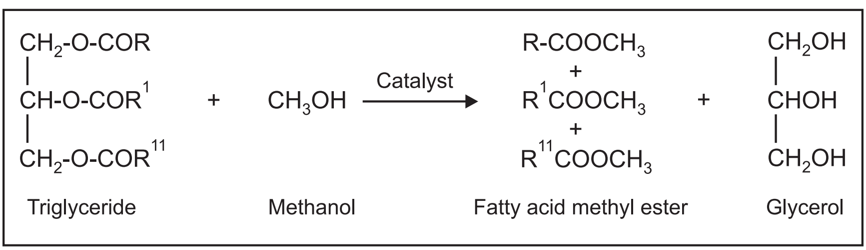
Dilution of vegetable oils can be accomplished with such materials as diesel fuels, solvent or ethanol.

## *Transesterification*

Transesterification, also called alcoholysis, is the displacement of alcohol from an ester by another alcohol in a process similar to hydrolysis. This process has been widely used to reduce the viscosity of triglycerides. The transesterification reaction is represented by the general equation:

$$RCOOR' + R'' \rightarrow RCOOR'' + R¢OH$$

If methanol is used in the above reaction, it is termed methanolysis. The reaction of triglyceride with methanol is represented by the general equation:



Triglycerides are readily trans-esterified in the presence of alkaline catalyst at atmospheric pressure and at a temperature of approximately 60–70°C with an excess of methanol. The mixture at the end of reaction is allowed to settle. The lower glycerol layer is drawn off while the upper methyl ester layer is washed to remove entrained glycerol and is then processed further. The excess methanol is recovered by distillation and sent to a rectifying column for purification and recycled.

The transesterification works well when the starting oil is of high quality. However, quite often low quality oils are used as raw materials for biodiesel preparation. In cases where the free fatty acid content of the oil is above 1 per cent, difficulties arise due to the formation of soap which promotes emulsification during the water washing stage and at an FFA content above 2 per cent the process becomes unworkable.

### 22.3.3 Process variables in transesterification

The most important variables that influence transesterification reaction time and conversion are:

1. Oil temperature
2. Reaction temperature
3. Ratio of alcohol to oil
4. Catalyst type and concentration
5. Mixing intensity
6. Purity of reactants

#### *Oil temperature*

The temperature to which oil is heated before mixing with catalyst and methanol, affects the reaction. It was observed that increase in oil temperature marginally increases the percentage oil to biodiesel conversion as well as the biodiesel recovery. However, the tests were conducted up to only 60°C as higher temperatures may result in methanol loss in the batch process.

#### *Reaction temperature*

The rate of reaction is strongly influenced by the reaction temperature. Generally, the reaction is conducted close to the boiling point of methanol (60°C to 70°C) at atmospheric pressure. The maximum yield of esters occurs at temperatures ranging from 60°C to 80°C at a molar ratio (alcohol to oil) of 6:1. Further increase in temperature is reported to have a negative effect on the conversion. Studies have indicated that given enough time, transesterification can proceed satisfactorily at ambient temperatures in the case of the alkaline catalyst. It was observed that biodiesel recovery was affected at very low temperatures (just like low ambient temperatures in cold weather) but conversion was almost unaffected.

### Ratio of alcohol to oil

Another important variable affecting the yield of ester is the molar ratio of alcohol to vegetable oil. A molar ratio of 6:1 is normally used in industrial processes to obtain methyl ester yields higher than 98 per cent by weight. Higher molar ratio of alcohol to vegetable oil interferes in the separation of glycerol. It was observed that lower molar ratios required more reaction time. With higher molar ratios, conversion increased but recovery decreased due to poor separation of glycerol. It was found that optimum molar ratios depend upon type and quality of oil.

### Catalyst type and concentration

Alkali metal alkoxides are the most effective transesterification catalyst compared to the acidic catalyst. Sodium alkoxides are among the most efficient catalysts used for this purpose, although potassium hydroxide and sodium hydroxide can also be used. Transmethylations occur many folds faster in the presence of an alkaline catalyst than those catalysed by the same amount of acidic catalyst. Most commercial transesterifications are conducted with alkaline catalysts. The alkaline catalyst concentration in the range of 0.5 to 1 per cent by weight yields 94–99 per cent conversion of vegetable oil into esters. Further, increase in catalyst concentration does not increase the conversion and it adds to extra costs because it is necessary to remove it from the reaction medium at the end.

It was observed that higher amounts of sodium hydroxide catalyst were required for higher FFA oil. Otherwise higher amount of sodium hydroxide resulted in reduced recovery.

### Mixing intensity

The mixing effect is most significant during the slow rate region of the transesterification reaction. As the single phase is established, mixing becomes insignificant. The understanding of the mixing effects on the kinetics of the transesterification process is a valuable tool in the process scale-up and design. It was observed that after adding methanol and catalyst to the oil, 5–10 minutes stirring helps in higher rate of conversion and recovery.

### *Purity of reactants*

Impurities present in the oil also affect conversion levels. Under the same conditions, 67–84 per cent conversion into esters using crude vegetable oils can be obtained, compared with 94–97 per cent when using refined oils. The free fatty acids in the original oils interfere with the catalyst. However, under conditions of high temperature and pressure this problem can be overcome.

It was observed that crude oils were equally good compared to refined oils for production of biodiesel. However, the oils should be properly filtered. Oil quality is very important in this regard. The oil settled at the bottom during storage may give lesser biodiesel recovery because of accumulation of impurities like wax, etc.

## 22.3.4 Raw material and its quality for the production of biodiesel

### *Vegetable oil*

Any sediment would collect at the bottom of the reaction vessel during glycerol settling and at the liquid interface during washing. This would interfere with the separation of the phases and may tend to promote emulsion formation. The oil must be moisture-free because every molecule of water destroys a molecule of the catalyst thus decreasing its concentration. The free fatty acid content should be less than 1 per cent.

It was observed that lesser the FFA in oil better is the biodiesel recovery. Higher FFA oil can also be used but the biodiesel recovery will depend upon oil type and amount of sodium hydroxide used.

### *Alcohol*

Methanol or ethanol, as near to absolute as possible. As with the oil, the water affects the extent of conversion enough to prevent the separation of glycerol from the reaction mixture.

### *Catalyst*

Sodium or potassium hydroxide, preferably the latter. The corresponding alkoxide also can be used, but prohibitively expensive. Best if it has ≥85 per cent potassium hydroxide. Even best grades of potassium hydroxide have 14–15 per cent water which cannot be removed. It should be low in carbonate, because the carbonate is not an efficient catalyst and may cause cloudiness in the final ester. Sodium hydroxide pellets have given very good results.

Because quantity of catalyst used is quite less, good quality catalyst (in spite of high cost) can be used.

### *Animal fats*

The most prominent animal fat to be studied for potential biodiesel use is tallow. Tallow contains a high amount of saturated fatty acids, and it has therefore a melting point above ambient temperature.
Waste vegetable oils

Every year many millions of tons of waste cooking oils are collected and used in a variety of ways throughout the world. This is a virtually inexhaustible source of energy, which might also prove an additional line of production for 'green' companies. These oils contain some degradation products of vegetable oils and foreign material. However, analyses of used vegetable oils indicate that the differences between used and unused fats are not very great and in most cases simple heating and removal by filtration of solid particles suffices for subsequent transesterification. The cetane number of a used frying oil methyl ester was given as 49, thus comparing well with other materials.

### *Esters of vegetable oil*

They make good biomass fuels as diesel substitutes, provided the following factors receive special attention:

1. The yield of transesterified product should be >90 per cent.
2. The fuel should be as neutral as possible (pH 6.5–8.0).
3. The fuel should be centrifuged at a temperature below the expected ambient operating temperature. Winterisation has been suggested as the ideal solution.
4. The neutralising agent should form fuel in soluble salts, free from carbonate groups.
5. Ash content should be 0.01 per cent. The fuel should be free from alcohol.

## 22.3.5 Storability of biodiesel

It was observed that when the biodiesels of different oils were stored, their FFA as well as viscosity increased. However, FFA remained below 1 per cent even after one and a half years of storage. Minimum increase was observed in Jatropha curcas oil biodiesel followed by rice bran, sun flower and linseed oil biodiesel. During storage, the biodiesels also gained some weight. It may be mainly due to reaction with oxygen in the air.

## 22.4 Blending of esters and diesel

Blending conventional diesel fuel (DF) with esters (usually methyl esters) of vegetable oils is presently the most common form of biodiesel. The most common ratio is 80 per cent conventional diesel fuel and 20 per cent vegetable oil ester, also termed 'B20', indicating the 20 per cent level of biodiesel. There have been numerous reports that significant emission reductions are achieved with these blends.

No engine problems were reported in larger-scale tests with, for example, urban bus fleets running on B20. Fuel economy was comparable to DF2, with the consumption of biodiesel blend being only 2–5 per cent higher than that of conventional DF. Another advantage of biodiesel blends is the simplicity of fuel preparation, which only requires mixing of the components. Ester blends have been reported to be stable, for example, a blend of 20 per cent peanut oil with 80 per cent DF did not separate at room temperature over a period of 3 months. A 50:50 blend of peanut oil with DF was also found quite stable. Several studies have shown that diesel/biodiesel blends reduce smoke opacity, particulates, unburnt hydrocarbons, carbon dioxide and carbon monoxide emissions, but nitrous monoxide emissions are slightly increased. One limitation to the use of biodiesel is its tendency to crystallise at low temperatures below 0°C. Methyl and ethyl esters of vegetable oils will crystallise and separate from diesel at temperatures often experienced in winter time operation. Such crystals can plug fuel lines and filters, causing problems in fuel pumping and engine operation. One solution to this problem may be the use of branched-chain esters, such as isopropyl esters. The isopropyl esters of soyabean oil crystallise 7–11°C lower than the corresponding methyl esters. Another method to improve the cold flow properties of vegetable oil esters is to remove high-melting saturated esters by inducing crystallisation with cooling, a process known as winterisation.

## 22.5 Storage of biodiesel

Pure plant oils are completely harmless to the environment, especially the groundwater. However, esterification of vegetable oil increases its water hazard. As per German EPA classifies waste vegetable oil as a toxic waste. As a general rule blends of biodiesel and petroleum diesel should be treated like petroleum diesel. It is recommended to store biodiesel in clean, dry and approved tanks. Though the flash point of biodiesel is high, still storage precautions somewhat like that in storing the diesel fuel need to be taken biodiesel can be stored for long periods in closed containers with little headroom but the container must be protected from direct sunlight, low temperature and weather.

Underground storage is preferred in cold climates but is stored in open proper insulation; heating and other equipment should be installed. B20 fuel can be stored in above ground tanks depending on the pour point and cloud points of the blend. Low temperature can cause biodiesel to gel. Additives can be used for low temperature storage and pumping. The biodiesel/its blends should be stored at temperatures at least higher by 15°C that the pour point of the fuel. While splash blending the biodiesel, care should be taken to avoid very low fuel temperatures as the saturated compounds can crystallise and separate out to cause plugging of fuel lines and filters. Condensation of water in the tank should be avoided as hydrocarbon-degrading bacteria and mould can grow and use biodiesel as food.

Biodiesel and its blends are susceptible to growing microbes when water is present in fuel. Biocides, chemical that kill bacteria and moulds growing in fuel tank, in small concentration. Biocides do not remove sediments. Moreover, storage of biodiesel in old tanks can release accumulated deposits and slime and can cause very severe filter and pump blockage problem.

For long-term storage stability of biodiesel and blends adequate data are not available. Based on experience so far, it is recommended that biodiesel can be store up to a maximum period of 6 months. Some anti-oxidant additives are also used for longer periods of storage. Similarly periods are applicable for storage of biodiesel and its blends in vehicle fuel tank. Due to being a mild solvent, biodiesel has a tendency to dissolve the sediments normally encountered in old tanks used for diesel fuel and cause filter blockage, injector failures in addition to clogging of fuel lines. Brass, copper, zinc, etc. oxidise diesel and biodiesel fuels and create sediments. The fuel and fitting will start changing color as the sediments are formed. Storage tank made of aluminium, steel, etc. should be used.

## 22.6 Handling of biodiesel

As a general rule blends of biodiesel and petroleum diesel should be treated like petroleum diesel. Biodiesel vegetable methyl esters contain no volatile organic compounds that can give rise to poisonous or noxious fumes. There is no aromatic hydrocarbon (benzene, toluene, zylene) or chlorinated hydrocarbons. There is no lead or sulphur to react and release any harmful or corrosive gases. However, in case of biodiesel blends significant fumes released by benzene and other aromatics present in the base diesel fuel can continue.

On eye contact biodiesel may cause eye irritation. Safety glasses or face shields should be used to avoid mist or splash on face and eyes. Fire fighting measures to be followed as per its fire hazard classification. Hot fuel may cause burn. Biodiesel should be handled with gloves as it may cause soft skin. Mild irritation on skin can occur.

German regulations on water hazard classification classify products either as NWG (nonhazardous to water) or WGK 1, WGK 2 and WGK 3 with increasing water hazard. Both biodiesel and methanol are classifies as WGK 1. The glycerine also falls under same classification. There is no risk of explosions from vapour in biodiesel as the flash point is high and the vapour pressure is less than 1 mm Hg. Large biodiesel spills can be harmful. Biodiesel, while not completely harmless to the larvae of crustacea and fish, is less harmful than petroleum diesel fuel.

Biodiesel methyl esters have very low solubility in water (saturation concentration of 7 ppm in sea water and 14 ppm in freshwater at 17°C) compared to petroleum diesel that contain benzene, toluene, zylene and other more water soluble, highly toxic compounds. However, when the biodiesel is vigorously blended into water, the methyl esters form a temporary emulsion of tiny droplets that appear to be harmful to the swimming larvae. The half-life for biodegradation of vegetable methyl ester is about 4 days at 17°C about twice fast as petroleum diesel. In the laboratory tests, rapeseed methyl ester degraded by 95 per cent while the diesel fuel degraded only 40 per cent at the end of 23 days.

Any accidental discharge/spill of small amounts of biodiesel should have little impact on the environment compared to petroleum diesel, which contain more toxic and more water-soluble aromatics. Nonetheless, the methyl esters could still cause harm. EPA still considers spills of vegetable oils and animal fats as harmful to the environment. Spilling biodiesel in water is as illegal as spilling petroleum. Biodiesel need to be handled like any other petroleum fuels and laws should be reviewed to ensure that biodiesel is covered in the same class, if not included already. When biocides are used in the fuel tank to kill bacteria, suitable handling precautions like use of gloves and eye protection is must.

One must check if the laws on disposal of petroleum products are applicable to biodiesel also. Similarly check if laws for spill prevention and containment action for those who produce or store biodiesel exists. Discharge of animal fats and vegetable oil are order of magnitude less toxic than petroleum discharge, do not create carcinogenic compounds and, are really biodegradable by bacteria thus minimising physical impact on environment.

Nevertheless, extreme discharges of animal fats, vegetable oils and biodiesel can cause negative impact on aquatic life. Biodiesel spills compare more favourably to petroleum oil spills. Moreover, likelihood of vegetable oil or biodiesel oil spill being comparable in magnitude to a petroleum spill is also very small due to differences in volumes in the two industries. Petroleum tankers exceed 2,50,000 ton capacity whereas vegetable oils are carried in parcel tankers with 3500 ton capacity.

There is a need to differentiate between the vegetable oils and petroleum oil through the creation of separate classes for animal fats and vegetable oils from petroleum oils, and apply separate standards based on the differences in physical characteristics between the classes. Biodiesel is currently controlled in the same manner as animal fats, vegetable oils and petroleum oils are controlled under oil spill laws and regulations, biodiesel facilities and tanker vessels transporting biodiesel remain controlled in the same manner as if they were petroleum oil facilities or tanker vessels transporting petroleum oil.

## 22.7 Analysis of technologies with reference to Indian resources and requirements

India has rich and abundant forest resources with a wide range of plants and oilseeds. The production of these oilseeds can be stepped up many folds if the government takes the decision to use them for producing diesel fuels. Economical feasibility of biodiesel depends on the price of the crude petroleum and the cost of transporting diesel to long distances to remote markets in India. Further, the strict regulations on the aromatics and sulphur contents in diesel fuels will result in higher cost of production of conventional diesel fuels.

The production of ethyl esters from edible oils is currently much more expensive than hydrocarbon-based diesel fuels due to the relatively high costs of vegetable oils. The cost of biodiesel can be reduced if we consider nonedible oils, and used frying oils instead of edible oils. Nonedible oils such as neem, mahua, karanja, babassu, Jatropha, etc. are easily available in many parts of the world including India, and are very cheap compared to edible oils. The potential availability of some nonedible oils in India is given in Table 22.1.

**Table 22.1** Nonedible oil sources of India.

| Oil | Botanical | Potential (million tons) | Utilised (million tons) | Per cent utilisation |
|---|---|---|---|---|
| Rice bran | *Oryza sativa* | 4,74,000 | 1,01,000 | 21 |
| Sal | *Shorea robusta* | 7,20,000 | 23,000 | 3 |
| Neem | *Melia azadirachta* | 4,00,000 | 20,000 | 6 |
| Karanja | *Pongamia glabra* | 1,35,000 | 8000 | 6 |

The processing of oilseeds for the production of edible vegetable oils generates by-product streams containing triglycerides, phospholipids and free fatty acids. In many cases these streams are of considerably lower value than the finished oil. Successful development of a scheme for ester synthesis from low-value lipids could address the economic barriers to a wider adoption of biodiesel.

Fatty acid methyl ester could be produced from tall oil, a by-product in the manufacture of pulp by the Kraft process. Tall oil consists of free C18 unsaturated fatty acids, resin acids and relatively small amounts of unsaponifiables. The fatty acid fraction of tall oil contains mainly oleic acid, linoleic acid and its isomers. With the mushrooming of fast food centres and restaurants in India, it is expected that considerable amounts of used-frying oils will be discarded into the drains. These can be used for making biodiesel, thus helping to reduce the cost of water treatment in the sewerage system and assisting in the recycling of resources.

Acid oil, which is cheaper than both raw and refined oils, is a major by-product of the alkali refining industries and is a potential raw material for making biodiesel. It is also possible to use vegetable oils directly blended with diesel oil. With about 25 per cent diesel oil mixed with vegetable oil, it is possible to achieve improved thermal efficiency and lower smoke emissions.

Heating the fuel to lower the viscosity and then using vegetable oils directly as fuels is also an option. Thermal and catalytic decomposition of vegetable oils to produce gasoline and diesel fuel has been studied by a number of scientists using various methods with the objective of finding a gasoline replacement, but the fuel obtained possessed an inferior octane number. At the present, a hydrocarbon fuel with a similar volatility and molecular weight as diesel fuel can be produced with an approximate volume yield of 50 per cent from the decomposition of vegetable oils. The method that appears most promising is prehydrogenation followed by thermal or catalytic decomposition of vegetable oils.

Biodiesel can be used as a pure fuel or blend with petroleum diesel depending on the economics and emissions. The Indian Scenario is different from Europe and USA where refined vegetable oils, waste frying oils and tallow are used to produce biodiesel. In India, nonedible oils are likely the preferred feedstock. The transesterification of nonedible oils has not been studied extensively with a view to produce biodiesel. Data on oil characteristics, their behaviour in transesterification and quality of biodiesel produced from each oil are needed for application of this process such as: catalysts (basic, acidic, homogeneous/heterogeneous); continuous/batch operation; scale of operation; by products valuation and utilisation.

## 22.8 Engine development and modifications

Studies conducted with biodiesel on engines have shown substantial reduction in particulate matter (25–50 per cent). However, a marginal increase in NOx

(1–6 per cent) is also reported. It may be noted that the marginal increase in NOx can be taken care of either by optimisation of engine parts or by using De-NOx catalyst. HC and CO emissions were also reported to be lower. Nonregulated emissions like PAH, etc. were also found to be lower. Although, biodiesel is reported to have superior lubricity, its effect on lubricity of FIP needs to be quantified for typical Indian feed stocks. Flash point of biodiesel is high (>100°C). Its blending with diesel fuel can be utilised to increase the flash point of diesel particularly in India where flash point is 35°C well below the world average of 55°C. This is important from the safety point of view. Most of the studies reported had used methyl ester. However, ethyl ester can also be expected to give similar results. The viscosity of biodiesel is higher (1.9 to 6.0 cSt) and reported to result into gum formation on injector, cylinder liner, etc. This needs to be studied on various engine designs. 5–10 per cent biodiesel can be used with HSD without any engine modifications. It may be noted that increasing demand on improving fuel quality with time due to stringent emission norms requires heavy cost in terms of better vehicle technology and refineries upgradation. Therefore, use of clean fuels like biodiesel becomes more relevant in the present context.

Biodiesel can be derived from many vegetable oils, restaurant greases and fats such as corn, cashew, oat, palm, lupine, rubber seed, coffee, linseed, hazelnut, euphobia, pumpkin seed, sesame, kenaf, calendula, cotton, hemp, soyabean, rapeseed, olive tree, castor bean, jojoba, pecan, oil palm, safflower, rice, sunflower, peanut, tung oil tree, jatropha, macadamia nut, brazil nut, avocado, coconut, macuba palm karanja, etc. Vegetable oils can be used as a fuel in diesel engines. The use of unrefined vegetable oil leads to poor fuel atomisation due to high viscosity resulting in poor combustion and also more gum formation in fuel injector, liner, etc. The results of emissions of using unrefined vegetable oils were unfavourable and were also accompanied by deposit formation. Therefore, it is necessary to esterify the vegetable oil for use in engines. Most of the studies presented below are focused on use of methyl ester and its blends in engines. Methyl esters have high cetane number leading to low engine operating noise and good starting characteristics.

Engine oil dilution is a potential problem with biodiesel since it is more prone to oxidation and polymerisation than diesel fuel. The presence of biodiesel in engine could cause thick sludge to occur with the consequence that the oil becomes too thick to pump. Engine oil formulations need to be studied to minimise the effect of dilution with biodiesel.

The manufacture of caterpillar engine has recommended various suggestions to the users on the use of biodiesel in their engines. The salient features of recommendations are:

1. Biodiesel provides approximately 5–7 per cent less energy than distillate fuels. One should not change the engine rating to compensate for the power loss in order to avoid engine problems.
2. At low ambient temperatures, the fuel system may require heated fuel lines, filters and tanks. Biodiesel has poor oxidation stability, which may accelerate fuel oxidation in the fuel system. Oxidation stability additive has to be used to avoid long-term storage problem.
3. They have set the caterpillar biodiesel specification standards. In that, they mentioned the fuel quality on use in caterpillar engine should be sulphur content maximum of 0.01 per cent by weight, cetane number minimum of 45, flash point minimum of 100°C, etc.

## 22.9 Environmental and health effects of biodiesel

The use of biodiesel in a conventional diesel engine results in substantial reduction of unburned hydrocarbons, carbon monoxide and particulate matter. However, emissions of nitrogen dioxides are either slightly reduced or slightly increased depending on the duty cycle and testing methods. The use of biodiesel decreases the solid carbon fraction of particulate matter (since the oxygen in biodiesel enables more complete combustion to $CO_2$), eliminates the sulphur fraction (as there is no sulphur in the fuel), while the soluble or hydrogen fraction stays the same or is increased. Therefore, biodiesel works well with new technologies such as oxidation catalysts.

The life-cycle production and use of biodiesel produces approximately 80 per cent less carbon dioxide and almost 100 per cent less sulphur dioxide compared to conventional diesel.

Biodiesel emissions are nontoxic and it is clear that biodiesel gives a distinct emission benefit almost for all regulated and non-regulated pollutants when compared to conventional diesel fuel but emissions of $NO_x$ appear to increase from biodiesel. $NO_x$ increases with the increase in concentration of biodiesel in the mixture of biodiesel and petrodiesel. This increase in $NO_x$ emissions may be neutralised by the efficient use of $NO_x$ control technologies, which fits better with almost nil sulphur biodiesel than conventional diesel containing sulphur. It may also be noted that emission of $NO_x$ also varies with the different family of feedstocks for biodiesel. Moreover, the problem of increased $NO_x$ emission can be effectively tackled by retarding the fuel injection timing.

## 22.10 Comparison of particulate composition—diesel vs. biodiesel (rapeseed methyl esters, RSME)

When the engine is operated on RSME, soot emissions (insolubles) are dramatically reduced, but the proportion of emissions composed of fuel-derived hydrocarbons (fuel solubles), condensed on the soot, is much higher. This implies that the RSME may not burn to completion as readily as diesel fuel. It should, however, be noted that gaseous HC emissions were reduced with RSME in the above tests. Since concern over particulates arises partly from the potential harmful effects of the soluble fraction, it might be suspected that emissions from RSME would be more harmful however data shows no tendency for the mutagenicity of exhaust gas to increase for a vehicle running on 20 per cent RSME and 80 per cent diesel blends.

### 22.10.1 Toxicity and safety issues

Biodiesel is nontoxic. The acute oral LD50 (lethal dose) is greater than 17.4 g/kg body weight. It causes very mild human skin irritation which is less than the irritation produced by 4 per cent soap and water solution. It is biodegradable. There is no tendency for the mutagenicity of exhaust gas to increase for a vehicle running on biodiesel (20 per cent RSME, 80 per cent diesel). Biodiesel is considered as fairly safer fuel. Biodiesel has a flash point of about 300°F well above conventional diesel fuel. The National Institute for Occupational Safety and Health (NIOSH), USA lists its aquatic toxicity as ‘insignificant’ in its registry of the toxic effects of chemical substances. EPA rates biodiesel to have the same safety concerns to that associated with conventional fuels. This product (biodiesel) is not ‘hazardous’ under the criteria of the Federal OSHA Hazard Communication Standard 29 CFR 1910.1200. As per the California Proposition 65, this product contains no chemicals known to the state of California to cause cancer. This fuel is registered under Fuel and Fuel additives at 40 CFR79 of US-EPA.

## 22.11 Biodiesel from Karanja oil

At a time when society is becoming increasingly aware of the declining reserves of oil for the production of fossil fuels, it has become apparent that biofuels are destined to make a substantial contribution to the future energy demands of the domestic and commercial economies.

The soaring prices of petroleum and the growing environmental concern to limit the exhaust emissions have led to emergence of biodiesel as an alternative to diesel fuels. Many vegetable oils, animal fats and even waste cooking oils are used to produce biodiesel. Vegetable oil (either edible or non-edible), when processed to remove fatty acids, gives biodiesel. To produce biodiesel, more plantations will be required, which will make the earth greener and help arrest ozone depletion. Use of biodiesel will reduce emission and air pollution substantially. Moreover, biodiesel is a renewable source of energy.

Nonedible oils like karanja can be used for the production of biodiesel.

Karanja has enormous potential for biodiesel production in India. India is a tropical country and offers most suitable climate for the growth of Karanja tree. It is found in abundance in rural areas and forests of entire India. As the tree of Karanja is naturally found in forests, there are so far no reports of adverse effects of karanja on flora, fauna, humans or even the environment.

Karanja oil has been reported to contain furanoflavones, furanoflavonols, flavones and furanodi-ketones, which make the oil nonedible and further encourages its application for biodiesel production. The biodiesel is developed from oil expelled from the seeds of the Karanja tree.

In our country, although presently Karanja, Jatropha and Castor are primarily considered for biodiesel, karanja has some advantages. Firstly, its origin is in India; hence it grows in all areas, all weather conditions, and all types of soils.

Transesterification of a vegetable oil was conducted as early as 1853, by scientists E. Duffy and J. Patrick, many years before the first diesel engine became functional. Rudolf Diesel's prime model, a single 10 ft (3 m) iron cylinder with a flywheel at its base, ran on its own power for the first time in Augsburg, Germany on August 10, 1893. In remembrance of this event, August 10 has been declared International biodiesel day.

Diesel later demonstrated his engine at the World Fair in Paris, France in 1898. This engine stood as an example of diesel's vision because it was powered by peanut oil. He believed that the utilisation of a biomass fuel was the real future of his engine. In a 1912 speech, Rudolf Diesel said, 'the use of vegetable oils for engine fuels may seem insignificant today, but such oils may become, in the course of time, as important as petroleum and the coal tar products of the present time'.

During the 1920s, diesel engine manufacturers altered their engines to utilise the lower viscosity of the fossil fuel (petrodiesel) rather than vegetable oil, a biomass fuel. The petroleum industries were able to make inroads in fuel markets because their fuel was much cheaper to produce than the biomass alternatives. The result was, for many years, a near elimination of the biomass fuel production infrastructure. Only recently have environmental impact concerns and a decreasing cost differential made biomass fuels, such as biodiesel, a growing alternative.

In the 1990s, France launched the local production of biodiesel fuel (known locally as diester) obtained by the transesterification of rapeseed oil. It was mixed to the proportion of 5 per cent into regular diesel fuel, and to the proportion of 30 per cent into the diesel fuel used by some captive fleets (public transportation). Renault, Peugeot and other manufacturers have certified truck engines for use with this partial biodiesel. Experiments with 50 per cent biodiesel are underway.

India imported about 2/3rd of its petroleum requirements, which involved a cost of approximately Rs. 80,000 crore in foreign exchange. Even 5 per cent replacement of petroleum fuel by biofuel can help India save Rs. 4000 crore per year in foreign exchange. The country has been hit hard by the increased cost and uncertainty and so is exploring other energy sources; biodiesel extracted from trees is one alternative under consideration. Physical properties of biodiesel are listed in Table 22.2.

**Table 22.2** Physical properties of biodiesel.

| Property | Value |
|---|---|
| Specific gravity | 0.87–0.89 |
| Kinematic viscosity @ 40°C | 3.7–5.8 |
| Cetane number | 46–70 |
| Higher heat value (Btu/lb) | 16928–17996 |
| Sulphur (wt%) | 0.02–0.0024 |
| Cloud point (°C) | –11 to 16 |
| Pour point (°C) | –15 to 13 |
| Iodine value/Number (gm) | 62–135 |
| Lower heating value (Btu/lb) | 15700–16735 |

From about 100 varieties of non-edible oilseed crops, only 10–12 varieties are most important for biodiesel production. In India, Jatropha, Karanja and Mahua trees has great potential for production of bio-fuels like bioethanol and biodiesel.

The annual estimated potential is about 20 mt. In India as on 2007, out of cultivated area, about 175 mn ha (million hectares) are classified as waste and degraded land; we can cultivate these crops very easily on this land.

Biodiesel is defined as the monoalkyl esters of fatty acids derived from vegetable oils or animal fats. In simple terms, biodiesel is the product you get when a vegetable oil or animal fat is chemically reacted with an alcohol to produce a fatty acid alkyl ester. A catalyst such as sodium or potassium hydroxide is required. Glycerol is produced as a by-product. Biodiesel is manufactured from plant oils, animal fats and recycled cooking oils.

The advantages of biodiesel are as follows:

1. It is renewable.
2. Since, it can be derived from treeborne oilseeds, it will encourage plantation, which will help create green earth and arrest ozone depletion.
3. It can reduce tailpipe emissions, including air toxics.

4. It is energy efficient; it can reduce global warming gas emissions.
5. It is nontoxic, biodegradable and suitable for sensitive environments.
6. Biodiesel flash point is very high, which makes it safe for storage and transportation.
7. Use of biodiesel will reduce emissions and air pollution substantially as biodiesel contains very insignificant or almost no sulphur and has excellent emission results as against normal diesel.
8. It can be used as a 20 per cent blend in most diesel equipment with no or only minor modification.
9. Use of biodiesel will fill the gap of increasing demand and diesel shortage created by depleting reserves of fossil fuels.

Biodiesel contains no petroleum, but it can be blended at any level with petroleum diesel to create a biodiesel blend or can be used in its pure form. Just like petroleum diesel, biodiesel operates in compression ignition (diesel) engine; which essentially require very little or no engine modifications because biodiesel has properties similar to petroleum diesel fuels. It can be stored just like the petroleum diesel fuel and hence does not require separate infrastructure. Table 22.3 lists important parameters of raw and transesterified Karanja oil.

**Table 22.3** Important parameters of raw and transesterified karanja oil.

| Parameter | Karanja raw oil | Transesterified karanja oil | EDIN 51606 |
|---|---|---|---|
| Density (g/cm$^3$ at 20°C) | 0.92 | 0.876 | 0.875–0.890 |
| Flash point (°C) | 174.1 | 183 | >110 |
| Cetane no. (ISO 5165) | 57.6 | – | >49 |
| Viscosity (mm$^2$/s at 40°C) | 41.06 | 5.7 | 3.5–5 (40°C) |
| Total glycerine (wt %) | – | 0.0797 | <0.250 |
| Free glycerine (wt %) | – | 0.015 | <0.202 |
| Phosphorus (ppm) | – | – | <10 |
| Sulphated ash (%) | 0.002 | 0.005 | <0.03 |
| Methanol (%) | – | – | <0.3 |

The use of biodiesel in conventional diesel engines results in substantial reduction of unburned hydrocarbons, carbon monoxide and particulate matters. Table 22.4 given ASTM specification D6751 for biodiesel (B 100). Biodiesel is considered clean fuel since it has almost no sulphur, no aromatics and has about 10 per cent built-in oxygen, which helps it to burn fully. Its higher cetane number improves the ignition quality even when blended in the petroleum diesel. Table 22.5 given comparison of Karanja, Jatropha and diesel oils. The main commodity sources for biodiesel in India can be nonedible oils obtained from plant species such as Jatropha Curcas (Ratanjyot), Pongamia Pinnata (Karanja), Calophyllum inophyllum (Nagchampa), Hevea brasiliensis (rubber), etc. Comparison between Jatropha and Karanja is given in Table 22.6.

**Table 22.4** ASTM specification D6751 for biodiesel (B 100).

| Properties | Value |
|---|---|
| Water and sediment | 0.050% by vol., max. |
| Kinematic viscosity at 40°C | 1.9–6.0 mm2/s |
| Ramsbottam carbon residue, % mass | 1.0 |
| Sulphated ash | 0.020% by mass, max. |
| Sulphur | 0.05% by mass, max. |
| Copper strip corrosion | No. 3 max. |
| Cetane | 47 min. |
| Carbon residue | 0.050% by mass, max. |
| Acid number – mg KOH/g | 80 max. |
| Free glycerine | 0.020% mass |
| Total glycerine (free glycerine and unconverted glycerides combined) | 0.240% by mass, max. |
| Phosphorous content | 0.001 max. % mass |
| Distillation | 90% at 36°C |

**Table 22.5** Comparison of Karanja, Jatropha and diesel oils.

| Property | Karanja oil | Jatropha oil | Diesel oil |
|---|---|---|---|
| Colour | Dark yellow | Light yellow | Colourless to amber |
| Viscosity (cp) at 30°C | 15 | 52.6/5.1 | 3.60 |
| Specific gravity (15°C/4°C) | 0.909 | 0.917/0.923 | 0.841/0.85 |
| Solidifying point (°C) | – | 2.0 | 0.14 |
| Cetane value | 57.6 | 51.0 | 47.8 |
| Flash point (°C) | 174.1 | 11–240 | 80 |
| Carbon residue (%) | 0.50 | 0.64 | <0.05 to <0.15 |
| Distillation (°C) | 356 | 284–295 | <350 to <370 |
| Sulphur (% mass) | 4.5 ppm | <1 ppm | 0.05 |

*Cont...*

*Cont...*

| Property | Karanja oil | Jatropha oil | Diesel oil |
|---|---|---|---|
| Calorific value (Kcal/kg) | 9076 | 9470.0 | 10170.0 |
| Acid value | 6.2 | 5.4 | – |
| Saponification value | 189 | 197 | – |
| Iodine value | 89.3 | 96.6 | <115 |
| Non-saponificable value | 4 | 0.5 | – |
| Refractive index at 40°C | 1.4785 | 1.4656 | – |

**Table 22.6** Comparison between Jatropha and Karanja.

| Particulars | Karanja | Jatropha |
|---|---|---|
| No. of plants per acre | 200 | 1000 |
| Plant life | 80–100 years | 40–60 years |
| Yield start | 6th year | 3rd year |
| Yield per plant | Minimum 20 kg | Up to 2.5 kg |
| Seed yield per acre | 4 tons (min.) | 2.5 tons |
| Earnings per acre | Rs. 24,000 (min.) | Rs. 15,000 |
| Oil yield per acre | 1 ton (25%) | 0.75 tons (30%) |
| Oil cake per acre | 3 tons | 1.75 tons |

### 22.11.1 Justification for selecting Karanja over Jatropha

There are many alternatives for biodiesel. India has also taken initiatives in this field and the world is looking to Indian biodiesel plans. Indian experts have identified many plants that can be used as source to biodiesel. For different agro-climatic situations they have suggested different types of plants. But ignoring these recommendations everywhere the promotion of single species, Jatropha, is in progress. No one is thinking about other alternatives in spite of the fact that its near relative Karanja (Pongamia pinnata) is having immense potential. From a scientific point of view, Karanja is far better than Jatropha.

Few people know that Jatropha is exotic plant, native to Tropical America. Karanja, in contrast, is a native plant, present in our homeland since generations. Modern research has proved that the introduction of a new component in any ecosystem affects the life of each and every component from top to bottom, i.e. from other plants to micro-organisms. Jatropha is known as a plant having a dominating nature. This plant is rich in allelochemicals. This is the reason the traditional healers of Chhattisgarh have named it as Raja Van (King Plant). It suppresses the growth of other plants. Due to its aggressive nature and harmful impact on flora it is declared as a problematic weed in many countries. Figure 22.1 shows the worldwide production and capacity of biodiesel [mt].

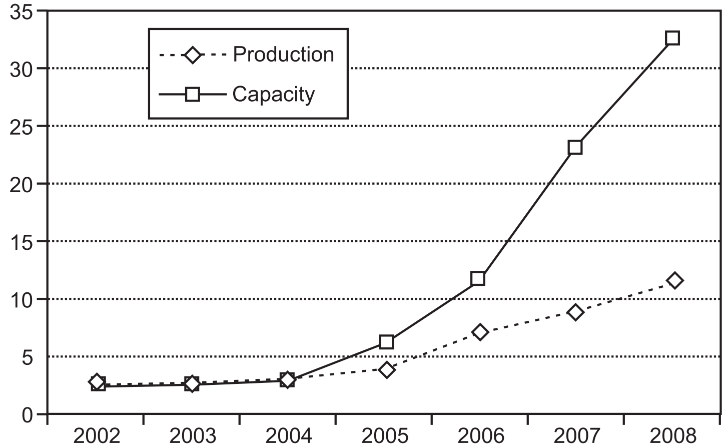



**Figure 22.1** Worldwide production and capacity of biodiesel (mt)

There is no such problem from Karanja. Karanja is an integral part of our ecosystem and it supports the growth of many plants, as well as micro-organisms. Jatropha, in contrast, is a poisonous plant. This is the reason there is a recommendation for its plantation in places far away from human population. Jatropha is a danger for small children. They like its tasty seeds very much. Four seeds are enough to take life. Table 22.7 given composition of Karanja and Jatropha oil seed cakes.

**Table 22.7** Composition of Karanja and Jatropha oilseed cakes.

| Constituent | Karanja | Jatropha |
|---|---|---|
| Oil (%) | 27.0 | 32.0 |
| Nitrogen/protein (wt %) | 4–7/25–40 | 4–6/25–40 |
| Carbohydrate (wt %) | 15–20/6.6 | 15–20/18 |
| Fibre (wt %) | 15–20/7.3 | 15–20/19.9 |
| Ash (wt %) | 3–5/2.3 | 3–5/4.1 |
| Acid insoluble ash (wt %) | 0.06 | 0.15 |
| Phosphorus (wt %) | 1–2 | 1.5–3 |
| Potassium (wt %) | 0.5–1.5 | 1–2 |

*Cont...*

*Cont...*

| Constituent | Karanja | Jatropha |
|---|---|---|
| Calcium (wt %) | <1 | <1 |
| Magnesium (wt %) | <0.5 | <1 |
| Zinc | Magnesium | Copper |
| Boron (ppm) | <100 | <100 |
| Sulphur (ppm) | <4000 | <3000 |
| Moisture (wt %) | 10.0 | 6.5 |

On the other hand, all plant parts of Karanja possess valuable medicinal properties. The reference literatures related to different systems of medicine in India, especially Ayurveda, are full of the therapeutic properties of karanja. In general, Jatropha starts giving commercial production three years after planting. In case of karanja, there is no need to wait for three long years. Millions of karanja trees are already present in India. We have not to invest millions of rupees for its plantation. The seed collection procedure will generate much employment opportunities. Planners are claiming that Jatropha plantation will generate much employment, but seeing its harm to public health it is not advisable from any angle to promote its plantation.

International experts have accepted that Jatropha biodiesel is costlier than conventional diesel and are seeking subsidy. Karanja biodiesel, on the other hand, is cheaper, ecofriendly and safe.

### 22.11.2 Manufacturing process

As mentioned earlier, the heating value of vegetable oil is almost similar to that of conventional diesel fuel, i.e. petroleum-based diesel fuel, but their use in diesel engine is restricted because of their high viscosity. The viscosity of vegetable oil is almost 10 times higher than the diesel fuel and use of highly viscous fuel in engines creates poor fuel atomisation, incomplete combustion, carbon deposition on injector and fuel build up in the lubricating oil resulting in engine fouling.

This necessitates improvement in viscosity of the biofuel, i.e. vegetable oil. The possible treatments that can be employed to improve the viscosity are:

1. Dilution of oil with a suitable solvent
2. Pyrolysis
3. Emulsification
4. Transesterification

## Dilution

Dilution of vegetable oils can be accomplished with such material as diesel fuels, solvent or ethanol.

## Pyrolysis

Pyrolysis refers to a chemical change caused by the application of thermal energy in the absence of air or nitrogen. The liquid fractions of the thermally decomposed vegetable oil are likely to approach diesel fuels. The pyrolysate has lower viscosity, flash point, and pour point than diesel fuel and equivalent calorific values. The cetane number of the pyrolysate is lower. The pyrolysed vegetable oils contain acceptable amounts of sulphur, water and sediment and give acceptable copper corrosion values, but unacceptable ash, carbon residue and pour point. Table 22.8 lists the comparison based on feedstock.

**Table 22.8** Comparison based on feedstock.

| Parameter | Karanja oil | Jatropha oil | Waste cooking oil |
|---|---|---|---|
| Oil sample used | Karanja | Jatropha | Waste cooking oil |
| Alcohol used | Methanol | Methanol | Methanol |
| Catalyst used | NaOH | NaOH | KOH |
| Reaction temperature (°C) | 55–60 | 55–60 | 30–70 |
| Reaction time (hour) | 1.5 | 1.0–1.5 | 0.5–1.2 |
| Settling time (hour) | 8–8.5 | 8–8.5 | – |
| Raw oil production (T/ha/yr) | 2.0–4.0 | 2.0–3.0 | – |
| Biodiesel production (per ha/year) | 1–3 | 1–1.5 | – |
| Seed yield per acre (T) | 4 T (min.) | 2.5 T | – |
| Oil (%) | 24–27 | 24.8 | – |
| Plant life (years) | 80–100 | 40–60 | – |
| Yield per plant | Min. 20 kg | Up to 2.5 kg | – |
| Earnings per acre (Rs.) | 24,000 (min.) | 15,000 | – |
| Oil cake/acre (T) | 3 | 1.75 (max.) | – |
| Maximum yield of biodiesel | 89.5% | 88–90% | 88% |
| Fuel consumptions | 49.54% | 62.75% | – |

## Microemulsification

The formation of microemulsions (co-solvency) is one of the potential solutions for solving the problem of vegetable oil viscosity. Microemulsions are defined as transparent, thermodynamically stable colloidal dispersions. The droplet diameters in microemulsions range from 100 to 1000 Å. A microemulsion can be made of vegetable oils with an ester and dispersant (co-solvent) or of vegetable oils, an alcohol and a surfactant and a cetane improver, with or without diesel fuels. Water (from aqueous ethanol) may also be present in order to use lower proof ethanol, thus increasing water tolerance of the microemulsions.

## *Transesterification*

Transesterification, also called alcoholysis, is the displacement of alcohol from an ester by another alcohol in a process similar to hydrolysis. This process has been widely used to reduce the viscosity of triglycerides. The transesterification reaction is represented by the general equation. RCOOR′ + R″ = RCOOR″ + R¢OH. If methanol is used in the above reaction, it is termed methanolysis. Triglycerides are readily transesterified in the presence of alkaline catalyst at atmospheric pressure and at a temperature of approximately 60–70°C with an excess of methanol.

The mixture at the end of reaction is allowed to settle. The lower glycerol layer is drawn off, while the upper methyl ester layer is washed to remove entrained glycerol and is then processed further. The excess methanol is recovered by distillation and sent to a rectifying column for purification and recycled.

Transesterification works well when the starting oil is of high quality. However, quite often low quality oils are used as raw materials for biodiesel preparation. In cases where the free fatty acid content of the oil is above 1 per cent, difficulties arise due to the formation of soap, which promotes emulsification during the water washing stage and at FFA content above 2 per cent the process becomes difficult.

Methanol is the preferred alcohol because it produces a more stable biodiesel reaction, is low cost, less affected by water and the transesterification reaction is faster compared with other alcohols.

Transesterification reaction can be achieved by following types of processes:

1. Alkali catalysed
2. Acid catalysed
3. Enzyme catalysed
4. Acid-base catalysed
5. Supercritical method

*Alkali catalysed method:* In the alkali catalysed process, the reaction is carried out at 60°C and 100 KPa. In this process, the methanol and anhydrous NaOH/KOH (catalyst) is initially mixed well to form a methoxide. Then methoxide (methanol along with the catalyst) and vegetable oil are charged into the reactor. The flow rates are adjusted to get a molar ratio of 6:1 of methanol to oil inside the reactor. The product stream from here is further sent for purification involving methanol recovery, FAME purification, glycerin purification and additional alkali removal.

*Acid catalysed method:* In the acid catalysed process the reactions are carried out at 80°C and 400 KPa and employs sulphuric acid as catalyst. In this process methanol and sulphuric acid are first mixed and methanol along with sulphuric acid and vegetable are charged to the reactor where a molar ratio of 4:2 of methanol to oil and a molar ratio of 1:3 of sulphuric acid to oil is maintained. The product containing FAME (biodiesel), unreacted reactants and glycerine are sent for further separation and purification treatments. The essence of this process, which makes it important, is its insensitivity to the presence of the fatty acid content in the oils, which affect the yield of biodiesel. Enzyme catalysed method: The reaction is carried out under enzymatic condition and usually a batch reactor is used. The reaction takes place slowly and requires at least 2–3 days to give 90 per cent yield, which makes it unsuitable for commercial or large-scale production.

*Acid–base catalysed reaction:* The reaction for acid-base catalysed process is carried out at the same ideal condition as that by acid catalysed and base catalysed process. It is used in a special case when the free fatty acid content of the oil is more than 5 per cent. This helps in reducing the free fatty acid contents to the acceptable limits and then base catalysed reaction can be carried out.

*Supercritical method:* This is a catalyst-free process, which involves the transesterification of triglycerides at high temperature and pressure condition. It even requires high molar ratio of alcohol to oil. In this method, oil and alcohol are charged in to an autoclave (HPV) reactor. Inside the reactor the main reaction take place at 350°C and 43 Mpa condition.

## Process selection

There are a number of parameters, which constitute the criteria in selecting the process. For the enzyme catalysed system, the reaction requires a much longer time. Hence it is not suited for large scale manufacturing purposes and its use is limited to laboratory scale purposes. The supercritical method requires high temperature and high pressure vessels, made from special alloys.

These vessels require large capital investments. Besides, their operating costs and maintenance costs are very high. In spite of the fact that the supercritical method is insensitive to free fatty acid and water content, this process will not be economical. Once again the economic and productivity aspects are not in the favour of the acid catalysed process. The increasing costs of acids, like sulphuric acid, is also responsible for the deterrence of this process.

Besides, it should be noted that the cost of potassium hydroxide and sodium hydroxide is comparatively less than that of sulphuric acid. In view of the above considerations, it may be concluded that the alkali-catalysed process is best suited for the production of biodiesel. This process satisfies most of the economic, commercial and practical requirements.

## *Process description*

The manufacturing process of biodiesel from Karanja can be divided into eight different sub processes. These are as follows:

*Oil preparation from seeds:* The seeds of Karanja are first dried (to remove moisture) and thereafter dehulled. The oil extraction can be done with hand or engine driven expellers. The resulting oil is filtered and sent for transesterification process. These are simple machines, which can be operated on village level and built within the country.

*Transesterification:* Transesterification process involves the reaction of triglycerides with methanol to form FAME. The process is carried out in a stainless steel reactor under prevailing condition of 60°C and 100 KPa. Fresh methanol, recycle methanol and anhydrous sodium hydroxide are mixed well in a mixer prior to being pumped into the reactor by pump. Simultaneously the Karanja oil is heated up to 60°C and the flow rate of the two streams are adjusted to maintain the molar ratio of methanol to oil as 6:1 in the reactor.

Due to the reversible nature of the reaction, the excess methanol helps in shifting the momentum of the reaction to right side. Almost 95 per cent conversion is obtained, i.e. 95 per cent of oil is converted into FAME, with glycerine as a by-product.

*Methanol recovery:* After the transesterification processes, the stream from the reactor, which is a mixture of unconverted oil, catalyst NaOH, product FAME, glycerine and methanol which is added in excess, is sent to a methanol distillation unit to recover the excess methanol. As the boiling point of methanol is 60°C, this is less than the boiling point of other constituents of the stream. Methanol is obtained as the distillate (top product). A reflux ratio of 2.5 is provided to assist better separation. Almost 94 per cent of the total methanol in stream is recovered after the process, which is then mixed with fresh methanol and charged back into to the reactor. Bottom stream is sent to washing column. Material of construction of the column is mild steel. Figure 22.2 shows the production process of biodiesel.

*Water washing:* The significance of this step is to facilitate the separation of FAME from glycerine, methanol and alkali catalyst NaOH. Since the gravity settler cannot be used alone due to imperfect separation of FAME, therefore the stream is initially treated with hot water at 60°C and the further sent to the gravity settler. The water washing column carries out a liquid-liquid extraction using hot water as a solvent and considered as the best way to obtain high purity and yield of FAME. The material of construction of the column is carbon steel. The stream from washing column containing FAME, water and traces of methanol and glycerine is sent to gravity settler where glycerine and alkali catalyst are removed as bottom stream.

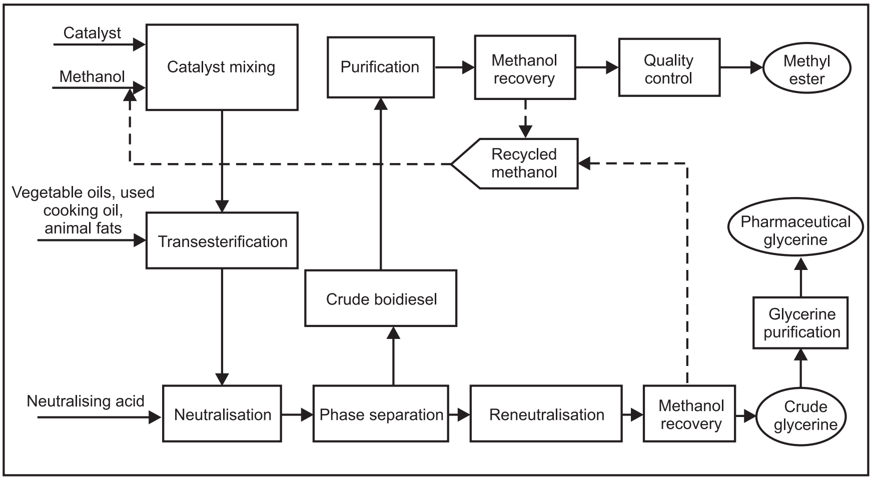



**Figure 22.2** The biodiesel production process

*FAME purification:* In order to obtain a final biodiesel product having ASTM specification (99.6 per cent pure) FAME distillation unit is employed. This unit operates under condition to keep temperatures low enough to prevent degradation of FAME. A partial condenser and reflux ratio of 2.5 provide good separation of FAME from methanol and water in column overhead. Water and methanol are removed as the vent gases and fame in stream as a liquid distillate at 194°C and 100 KPa.

*Alkali removal:* The bottom streams from washing column with a concentration of 81 per cent glycerine, 8 per cent water, 3 per cent methanol and 9 per cent sodium hydroxide is sent to neutralisation column to remove alkali catalyst by adding phosphoric acid (100 per cent pure). The material of construction of this neutralisation column is carbon steel. Further separation of resulting Na3PO4 is carried out in gravity settler. When potassium hydroxide is used as catalyst, the resulting potassium phosphate is used as a valuable by-product, e.g. fertiliser.

*Glycerine purification:* After the successful removal of alkali catalyst the remaining stream contains 24.4 per cent glycerine. To make higher-grade glycerine it is sent through the glycerine distillation unit for further removal of methanol and water as the top product. 41.1 per cent glycerine is obtained as a bottom product, which is sent for further purification. Material of construction for this distillation unit is carbon steel.

*Waste treatment:* Reusing the liquid wastes and gases can reduce the load of wastes treatment, e.g. water and methanol from glycerine purification unit can be used in washing column, instead of freshwater.

## 22.11.3 Factors affecting the process

### *Quality of feed oil*

It has been observed that crude vegetable oil is equally good compared to refined vegetable oils for the production of biodiesel. However, the oils need to be properly filtered. The oil quality is very important in this regard.

The oil settled at the bottom may give lesser biodiesel recovery because of accumulation of impurities like wax, etc. Impurities present in oil also affect the conversion of the oil.

### *Type of catalyst and concentration*

The alkali metal alkoxides are the most effective transesterification catalysts compared to the acid catalyst. Sodium alkoxides are the most commonly used catalysts for this purpose, although potassium hydroxide and sodium hydroxide can also be used.

Transmethylation occurs many times faster in presence of an alkaline catalyst than those catalysed by an equal amount of acidic catalyst.

The alkaline catalysts concentration in the range of 0.5–1 per cent (by weight); yields 94–99 per cent conversion of vegetable oils into esters.

### *Water content*

It is extremely significant that concentration of water in the raw material (vegetable oils) should remain below 0.06 per cent. The presence of water has a negative effect on the overall reaction, since the water present under alkaline condition leads to the formation of soaps, i.e. ester saponification, thereby consuming the catalyst and simultaneously deteriorating catalyst efficiency.

### *Free fatty acid content*

The free fatty acids reacts with the alkali catalyst to produce soaps and water saponification not only consumes the alkali catalyst, but also resultant soaps formed can lead to the formation of emulsions. This creates great difficulties in the separation and purification of FAME and makes the entire process unviable from economic aspect. Owing to these factors reasons it is therefore essential to ensure that the free fatty acid content should be kept under 0.5 per cent.

#### *Intensity of mixing*

The mixing effect is most significant during the slow rate region of the transesterification reaction. Once the single phase is established, mixing becomes insignificant. The understanding of mixing effects on the kinetics of transesterification process is a valuable tool in the process scale up and design. It has been observed that after adding methanol and catalyst to the oil, 5–10 minutes stirring helps in higher rate of conversion and recovery.

## 22.12 Biodiesel from microalgae beats bioethanol

Renewable biofuels are needed to displace petroleum derived transport fuels, which contribute to global warming and are of limited availability. Biodiesel and bioethanol are the two potential renewable fuels that have attracted the most attention. As discussed here, biodiesel and bioethanol produced from agricultural crops using existing methods cannot sustainably replace fossil-based transport fuels, but there is an alternative. Biodiesel from microalgae seems to be the only renewable biofuel that has the potential to completely displace petroleum-derived transport fuels without adversely affecting supply of food and other crop products. Most productive oil crops, such as oil palm, do not come close to microalgae in being able to sustainably provide the necessary amounts of biodiesel. Similarly, bioethanol from sugarcane is no match for microalgal biodiesel.

### 22.12.1 Crop-derived biodiesel and bioethanol are unsustainable

Carbon neutral renewable liquid fuels are needed to eventually totally displace petroleum-derived transport fuels that contribute to global warming. Biodiesel from oil crops and bioethanol from sugarcane are being produced in increasing amounts as renewable biofuels, but their production in large quantities is not sustainable. An alternative is offered by microalgae.

Microalgae are photosynthetic micro-organisms that convert sunlight, water and carbon dioxide to algal biomass. Many microalgae are exceedingly rich in oil, which can be converted to biodiesel using existing technology.

This chapter discusses the potential of microalgae for sustainably providing biodiesel for a complete displacement of petroleum-derived transport fuels, such as gasoline, jet fuel and diesel. In dramatic contrast with the best oil-producing crops, microalgal biodiesel has the potential to be able to completely displace petroleum-derived transport fuels without adversely impacting supplies of food and other agricultural products. It is further demonstrated that microalgal biodiesel is a better alternative than bioethanol from sugarcane, which is currently the most widely used transport biofuel.

Oil content of some microalgae exceeds 80 per cent of the dry weight of algae biomass. Agricultural oil crops, such as soyabean and oil palm, are widely being used to produce biodiesel; however, they produce oils in amounts that are miniscule (e.g. less than 5 per cent of total biomass basis) compared with microalgae. As a consequence, oil crops can provide only small quantities of biodiesel for blending with petroleum diesel at a level of a few per cent, but they are incapable of providing the large quantities of biodiesel that are necessary to eventually displace all petroleum-sourced transport fuels. For example, oil palm, one of the most productive oil crops, yields only ~5950 litres of oil per hectare. Biodiesel yield from a parent vegetable oil is ~80 per cent of the oil yield per hectare. A country such as the United States requires nearly 0.53 billion $m^3$ of biodiesel annually at the current rate of consumption, if all petroleum-derived transport fuel is to be replaced with biodiesel. To produce this quantity of biodiesel from palm oil, oil palm would need to be grown over an area of ~111 million (M) hectares. This is nearly 61 per cent of all agricultural cropping land in the United States. Growing oil palm at this scale would, therefore, be unrealistic, because insufficient land would be left for producing food, fodder and other crops. Based on these calculations, it is obvious that oil crops are not able to replace petroleum-derived liquid fuels in the foreseeable future. This scenario is, however, different if microalgae are used as a source of biodiesel. An average annual productivity of microalgal biomass in a well designed production system located in a tropical zone can be in the region of 1.535 kg $m^{-3}$ $d^{-1}$. At this level of biomass productivity, and if an average oil content of 30 per cent dry weight in the biomass is assumed, oil yield per hectare of total land area is ~123 $m^3$ for 90 per cent of the calendar year. (About 10 per cent of the year is unproductive, because the production facility must be shut down for routine maintenance and cleaning.) This amounts to a microalgal biodiesel yield of 98.4 $m^3$ per hectare. Therefore, producing the 0.53 billion $m^3$ of biodiesel the US needs as transport fuel, would require microalgae to be grown over an area of ~5.4 M hectares or only 3 per cent of the US cropping area. This is a feasible scenario even if the algal biomass contains only 15 per cent oil by dry weight. No other potential sources of biodiesel come close to microalgae in being realistic production vehicles for biodiesel. Another important advantage of microalgae is that, unlike other oil crops, they grow extremely rapidly and commonly double their biomass within 24 hours. In fact, the biomass doubling time for microalgae during exponential growth can be as short as 3.5 hours, which is significantly quicker than the doubling time for oil crops.

## 22.12.2 An integrated oil-production process

A conceptual process for producing microalgal oils for making biodiesel is shown in Fig. 22.3. The process consists of a microalgal biomass production step that requires light, carbon dioxide, water and inorganic nutrients. The latter are mainly nitrates, phosphates, iron and some trace elements. Seawater supplemented with commercial nitrate and phosphate fertilisers, and a few other micronutrients, is commonly used for growing marine microalgae.

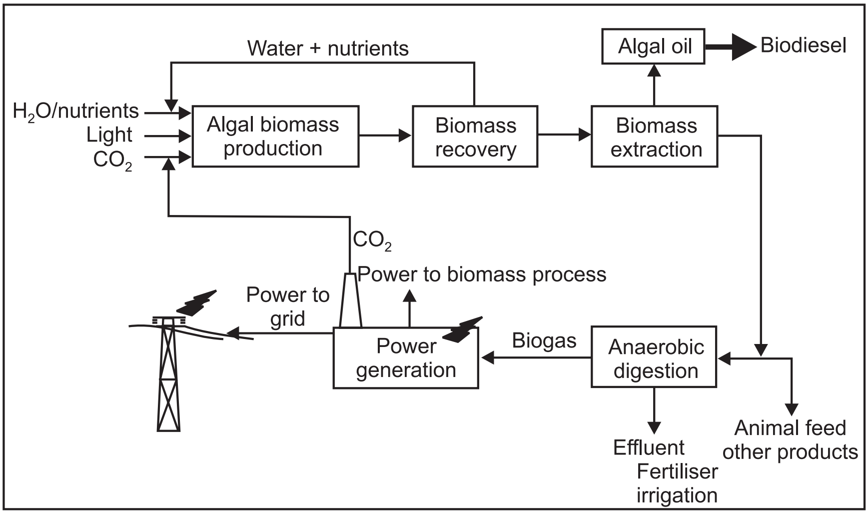



**Figure 22.3** A conceptual process for producing microalgal oil for biodiesel. Water, inorganic nutrients, carbon dioxide and light are provided to microalgal culture during the biomass-production stage. In the biomass-recovery stage, the cells suspended in the broth are separated from the water and residual nutrients, which are then recycled to the biomass-production stage. The recovered biomass is used for extracting the algal oil that is further converted to biodiesel in a separate process. Some of the spent biomass can be used as animal feed and for recovering other possible high value products that might be present in the biomass. Most of the biomass undergoes anaerobic digestion, which produces biogas to generate electricity. Effluents from the anaerobic digester are used as a nutrient-rich fertiliser and as irrigation water. Most of the power generated from the biogas is consumed within the biomass-production process and any excess energy is sold to grid. Carbon dioxide emissions from the power generation stage are fed into the biomass production.

Fresh and brackish water from lakes, rivers and aquifers can be used. Growth media are generally inexpensive. In a 100 tons per annum facility, cost of producing algal biomass has been estimated to be about \$3000 $ton^{-1}$, (year 2009) but cost per ton declines significantly as the scale of the production operation is increased.

Approximately half of the dry weight of the microalgal biomass is carbon, which is typically derived from carbon dioxide. Therefore, producing 100 tons of algal biomass fixes roughly 183 tons of carbon dioxide. This carbon dioxide must be fed continually during daylight hours. Microalgal biomass production can potentially make use of some of the carbon dioxide that is released in power plants by burning fossil fuels. This carbon dioxide is often available at little or no cost.

The algal broth produced in the biomass production stage needs to be further processed to recover the biomass. The water and residual nutrients recovered at this stage can be recycled to the biomass-cultivation stage (Fig. 22.3). The concentrated biomass paste is extracted with a water-immiscible solvent to recover algal oil, which can then be converted to biodiesel using already existing methods. The feasibility of oil extraction for microalgal biomass has been previously demonstrated. The extraction solvent (e.g. hexane) is expected to be recovered and recycled.

The biomass residue that remains after extraction of oil could be used partly as high-protein animal feed and, possibly, as a source of small amounts of other high-value microalgal products. In both scenarios, the revenue from selling the biomass residues could defray the cost of producing biodiesel. However, the majority of algal biomass residue from oil extraction is expected to undergo anaerobic digestion to produce biogas. This biogas will serve as the primary source of energy for most of the production and processing of the algal biomass. The generation of surplus energy is expected and this could be sold to grid to further improve the economics of the integrated process. Additional income could come from the sale of nutrient-rich fertiliser and irrigation water that would be produced during the anaerobic digestion stage (Fig. 22.3).

The technology for anaerobic digestion of waste biomass exists and is well developed, and the technology for converting biogas to electrical/mechanical power is well established. The carbon dioxide generated from combustion of biogas can be recycled directly for the production of the microalgae biomass (Fig. 22.3). Energy content of biogas produced through anaerobic digestion typically ranges from 16,200 kJ $m^{-3}$ to 30,600 kJ $m^{-3}$ depending on the nature of the source biomass. Typically, the yield of biogas varies from 0.15 to 0.65 $m^3$ per kg of dry biomass. Assuming average values of biogas energy content and yield, biogas production from microalgal solids, after their

30 per cent oil content has been removed, could provide at least 9360 MJ of energy per metric ton. This is a substantial amount of energy and it should run the microalgal biomass production process.

Ideally, microalgal biodiesel can be carbon neutral, because all the power needed for producing and processing the algae could potentially come from biodiesel itself and from methane produced by anaerobic digestion of the biomass residue left behind after the oil has been extracted. Although microalgal biodiesel can be carbon neutral, it will not result in any net reduction in carbon dioxide that has already accumulated as a consequence of burning of fossil fuels.

### 22.12.3 Production of microalgal biomass

Producing microalgal biodiesel requires large quantities of algal biomass. To minimise expense, the biomass must be produced using freely available sunlight and is thereby affected by fluctuations such as daily and seasonal variations in light levels. Microalgae can be grown on a large scale in photobioreactors. Many different designs of photobioreactors have been developed, but a tubular photobioreactor seems to be most satisfactory for producing algal biomass on the scale needed for biofuel production (Fig. 22.4).

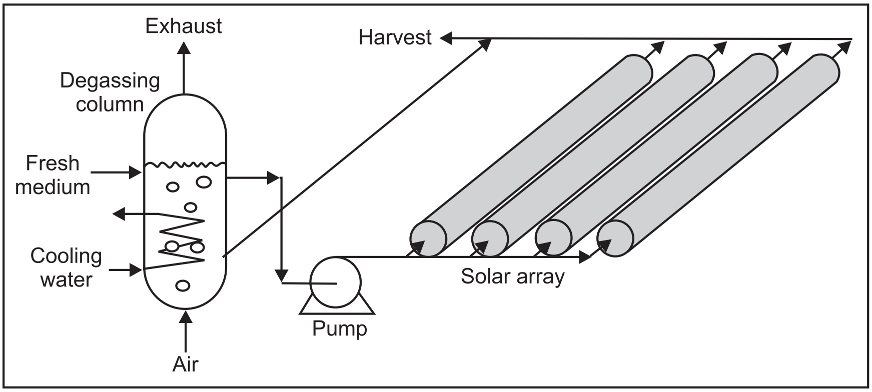



**Figure 22.4** A tubular photobioreactor with parallel run horizontal tubes

A tubular photobioreactor consists of an array of straight transparent tubes that are usually made of plastic or glass. This tubular array or the solar collector, captures the sunlight for photosynthesis (Fig. 22.4). The solar collector tubes are generally less than 0.1 m in diameter to enable the light to penetrate into a significant volume of the suspended cells. Microalgal broth is circulated from a reservoir (such as the degassing column shown in Fig.

22.4) to the solar collector and back to the reservoir. A photobioreactor is typically operated as a continuous culture during daylight. In a continuous culture, fresh culture medium is fed at a constant rate and the same quantity of microalgal broth is withdrawn continuously. Feeding ceases during the night; however, the mixing of broth must continue to prevent settling of the biomass. As much as 25 per cent of the biomass produced during daylight might be consumed during the night to sustain the cells until sunrise. The extent of this nightly loss depends on the light level under which the biomass was grown, the growth temperature and the temperature at night.

To maximise sunlight capture, the tubes in the solar collector are generally oriented North–South (Fig. 22.4). By arranging the tubes in a fence-like arrangement, shown in Fig. 22.4, the number of tubes that can be accommodated in a given area is maximised. The ground beneath the solar collector is either painted white or covered with white sheets of plastic to increase reflectance or albedo, which will increase the total light received by the tubes.

Biomass sedimentation in the tubes is prevented by maintaining a highly turbulent flow. This flow is produced either using a mechanical pump (as shown in Fig. 22.4) or a more gentle airlift pump, because mechanical pumps can damage the biomass. Airlift pumps have been used commonly because they are generally less expensive to install than mechanical pumps, cause less damage to biomass and do not have any moving parts that might fail; nevertheless, airlift pumps are less versatile than mechanical pumps and they can be difficult to design.

Photosynthesis generates oxygen. Under midday irradiance in most locations, the maximum rate of oxygen generation in a typical tubular photobioreactor can be as high as 10 g $O_2$ $m^{-3}$ $min^{-1}$. Dissolved oxygen levels that are much greater than air saturation values will inhibit photosynthesis. Furthermore, a high concentration of dissolved oxygen in combination with intense sunlight produces photo-oxidative damage to algal cells.

To prevent photosynthesis inhibition and cell damage, the maximum tolerable dissolved oxygen level should not exceed 400 per cent of air saturation value. Because accumulated oxygen cannot be removed within a photobioreactor tube, the maximum length of a continuous tube run is limited. To remove oxygen, the culture is periodically returned to a degassing zone in which it is aerated to strip out the accumulated oxygen (Fig. 22.4). Typically, a continuous tube run does not exceed 80 m; however, the possible tube length depends on several factors, including the concentration of the biomass, the light intensity, the flow rate and the concentration of oxygen at the entrance of the tube.

In addition to removing the accumulated dissolved oxygen, the degassing zone must disengage all the gas bubbles from the broth so that essentially bubble-free broth returns to the solar collector tubes. The presence of too many gas bubbles in the solar tubes will interfere with light absorption and reduce the flow of culture broth in the tubes. The design of potential gas–liquid separators that achieve complete disengagement of bubbles has been discussed. A major requirement for a degassing zone is that its volume is kept small relative to the volume of the solar collector. This is owing to the fact that degassing zones are generally optically deep compared with the solar collector tubes and poorly illuminated, therefore negatively affecting microalgae growth. Another factor that affects the performance of a photobioreactor is the pH of the culture.

As the broth moves along a photobioreactor tube, its pH increases because of consumption of carbon dioxide. To counteract this, carbon dioxide is fed in to the degassing zone in response to a pH controller. Furthermore, additional carbon dioxide injection points placed at intervals along the tubes can prevent carbon limitation and an excessive rise in pH.

Optimal temperature for growing many microalgae is between 20°C and 30°C. A temperature outside this range could kill or otherwise damage the cells. Algal broth in photobioreactor tubes exposed to sunlight will rapidly overheat, unless it is cooled. Cooling during daylight hours is essential. Furthermore, temperature control at night is also useful to prevent it from falling so low as to damage the cells. For example, the nightly loss of biomass owing to respiration can be reduced by lowering the temperature at night to a value that is a few degrees lower than the optimal growth temperature for a given alga. Outdoor tubular photobioreactors can be effectively and inexpensively cooled using heat exchangers, which can be placed in the degassing column, as shown in Fig. 22.4 or in the tubular loop. Evaporative cooling, using water sprayed on tubes, can also be used and has proven successful in dry climates, for example in Israel.

At least once a year, a photobioreactor facility must be shut down for routine maintenance and cleaning. Cleaning and sanitisation are required also in the event of failure of culture because of contamination with unwanted algae and parasites. A commercial photobioreactor must be capable of being cleaned rapidly to reduce downtime. Automated clean-in-place methods that do not require dismantling of the photobioreactor are generally used.

### 22.12.4 Better than bioethanol

It is useful to compare the potential of microalgal biodiesel with bioethanol from sugarcane, because on an equal energy basis, sugarcane bioethanol can be produced at a price comparable to that of gasoline. Bioethanol is well established for use as a transport fuel and sugarcane is the most productive source of bioethanol. For example, in Brazil, the best bioethanol yield from sugarcane is 7.5 $m^3$ per hectare. However, bioethanol has only ~64 per cent of the energy content of biodiesel. Therefore, if all the energy associated with 0.53 billion $m^3$ of biodiesel that the US needs annually was to be provided by bioethanol, nearly 828 million $m^3$ of bioethanol would be needed. This would require planting sugarcane over an area of 111 M hectares or 61 per cent of the total available cropping area of the United States.

Most of the energy needed for growing the cane and converting it to ethanol is gained from burning the cane crop waste or bagasse. For every unit of fossil energy that is consumed in producing cane ethanol, ~8 units of energy are recovered. A similar level of energy recovery seems to be possible for microalgal biodiesel. This is because in terms of total dry matter (including sugar), sugarcane typically yields ~75 metric tons of biomass per hectare and this is much less than 158 tons per hectare for microalgal biomass. Under absolute best conditions, sugarcane biomass yield does not exceed ~100 metric tons per hectare. For similar levels of energy in total biomass, a higher biomass production per hectare effectively translates to a higher amount of stored solar energy per hectare.

### 22.12.5 Prospects of microalgal biodiesel

Impediments to large-scale culture of microalgae are mainly economic. The economics of biodiesel production could be improved by advances in the production technology. Specific outstanding technological issues are efficient methods for recovering the algal biomass from the dilute broths produced in photobioreactors. Furthermore, extraction processes are needed that would enable the recovery of the algal oil from moist biomass pastes without the need for drying.

Algal biomass production capacity (i.e. the productivity) of a given photobioreactor facility depends on the geographical latitude where the facility is located. This is because the sunlight regimen varies with geographic location. For establishing the necessary size of the facility, the investment cost and operational expenses, anyone considering building an algal production facility needs to be able to calculate how much biomass and oil a facility will produce if it is located in a given region. Calculations such as this are not always reliable because of an insufficiently developed capability in photobioreactor engineering. Improved photobioreactor engineering will make predictions of productivity more reliable and enable design of photobioreactors that are more efficient.

A different and complimentary approach to increase productivity of microalgae is via genetic and metabolic engineering. Genetic and metabolic engineering are likely to have the greatest impact on improving the economics of production of microalgal diesel. This has been recognised since the 1990s, but little progress seems to have been made and genetic engineering of algae lags well behind that of bacteria, fungi and higher eukaryotes. Producing stable transformants of microalgae has proved difficult, although strategies for efficient transformation are being developed. Genetic and metabolic engineering in microalga has mostly focused on producing non-oil, high-value bioactive substances. This situation is likely to change because of a strong reemerging interest in sustainably produced biofuels. For example, molecular level engineering can be used potentially to: (i) enhance the photosynthetic efficiency and increase biomass yield on light, (ii) increase biomass growth rate, (iii) elevate the oil content in biomass, and (iv) improve temperature tolerance of algae so that there is a reduced need for cooling, which is expensive.

Another important factor that could be addressed by metabolic engineering is photoinhibition. Like plants, microalgae experience photoinhibition at high daylight levels, in that photosynthesis slows down once the light intensity has exceeded a certain value. Engineered algae that are either not photoinhibited or have a higher inhibition light threshold would significantly improve biodiesel production.

Industrial processes require inherently stable engineered strains and understanding of the methods that can be used to keep an otherwise unstable strain from losing its engineered characteristics is important, but barely known for microalgae.

## 22.12.6 Economics of biodiesel production

Recovery of oil from microalgal biomass and conversion of oil to biodiesel are not affected by whether the biomass is produced in raceways or photobioreactors. Hence, the cost of producing the biomass is the only relevant factor for a comparative assessment of photobioreactors and raceways for producing microalgal biodiesel.

### *Improving economics of microalgal biodiesel*

Cost of producing microalgal biodiesel can be reduced substantially by using a biorefinery-based production strategy, improving capabilities of microalgae through genetic engineering and advances in engineering of photobioreactors. Biorefinery-based production strategy

Like a petroleum refinery, a biorefinery uses every component of the biomass raw material to produce usable products. Because all components of the biomass are used, the overall cost of producing any given product is lowered.

Integrated biorefineries are already being operated in Canada, the United States, and Germany for producing biofuels and other products from crops such as corn and soyabean. This approach can be used to reduce the cost of making microalgal biodiesel.

In addition to oils, microalgal biomass contains significant quantities of proteins, carbohydrates and other nutrients. Therefore, the residual biomass from biodiesel production processes can be used potentially as animal feed (Fig. 22.5). Some of the residual biomass may be used to produce methane by anaerobic digestion, for generating the electrical power necessary for running the microalgal biomass production facility. Excess power could be sold to defray the cost of producing biodiesel.

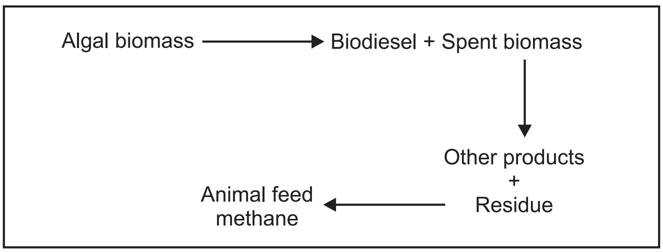



**Figure 22.5** Microalgal biodiesel refinery: Producing multiple products from algal biomass

Although the use of microalgal biomass directly to produce methane by anaerobic digestion is technically feasible, it cannot compete with the many other low-cost organic substrates that are available for anaerobic digestion. Nevertheless, algal biomass residue remaining after the extraction of oil can be used potentially to make methane. A microalgal biorefinery can simultaneously produce biodiesel, animal feed, biogas and electrical power (Fig. 22.5). Extraction of other high-value products may be feasible, depending on the specific microalgae used.

## *Enhancing algal biology*

Genetic and metabolic engineering are likely to have the greatest impact on improving the economics of production of microalgal diesel. Genetic modification of microalgae has received little attention. Molecular level engineering can be used to potentially:

1. Increase photosynthetic efficiency to enable increased biomass yield on light.
2. Enhance biomass growth rate.
3. Increase oil content in biomass.
4. Improve temperature tolerance to reduce the expense of cooling.
5. Eliminate the light saturation phenomenon so that growth continues to increase in response to increasing light level.
6. Reduce photoinhibition that actually reduces growth rate at midday light intensities that occur in temperate and tropical zones.
7. Reduce susceptibility to photo-oxidation that damages cells.

In addition, there is a need to identify possible biochemical triggers and environmental factors that might favour accumulation of oil. Stability of engineered strains and methods for achieving stable production in industrial microbial processes are known to be important issues, but have been barely examined for microalgae.

## *Photobioreactor engineering*

Although a capability for reliable engineering and operation of tubular photobioreactors has emerged, problems remain. Photobioreactor tubes operated with high-density culture for attaining high productivity, inevitably contain a photolimited central dark zone and a relatively better lit peripheral zone. Light intensity in the photolimited zone is lower than the saturation light level. Turbulence in the tube causes rapid cycling of the fluid between the light and dark zones.

The frequency of light–dark cycling depends on several factors, including the intensity of turbulence, concentration of cells, optical properties of the culture, the diameter of the tube, and the external irradiance level.

Under conditions of sufficient and excess external irradiance, light–dark cycling of above a certain frequency can increase biomass productivity relative to the case when the same quantity of light is supplied continuously over the same total exposure time. Light–dark cycling times of 10 ms, for example, are known to improve growth compared with continuous illumination of equal cumulative quantity. Beneficial effects of rapid light–dark cycling under light saturation conditions are associated with the short dark period allowing the photosynthetic apparatus of the cells to fully recover from the excited state of the previous illumination event.

Various attempts have been made to estimate the frequency of light–dark cycling, but this problem remains unresolved. Distinct from the productivity enhancing effect of light–dark cycling, turbulence in a dense culture reduces photoinhibition and photolimitation by ensuring that the algal cells do not reside continuously in either the well lit zone or the dark zone for long periods.

In principle, motionless mixers installed inside photobioreactor tubes can be used to substantially enhance the mixing between the peripheral lit zone and the interior dark zone. Such mixers have proved useful in other tubular reactors. Unfortunately, existing designs of motionless mixers are not satisfactory for photobioreactors because they substantially reduce penetration of light in the tubes. New designs of motionless mixers are needed.

Like cells of higher plants and animals, microalgae are damaged by intense hydrodynamic shear fields that occur in high-velocity flow in pipes, pumps and mixing tanks. Some algae are more sensitive to shear damage than others. Shear sensitivity can pose a significant problem as the intensity of turbulence needed in photobioreactors to generate optimal light–dark cycling is difficult to achieve without damaging algal cells. Methods have been developed to reduce the damage associated with turbulence of limited intensity. Intensities of shear stress are not easily determined in bioreactors, but improved methods for doing so are emerging. Some algae will preferentially grow attached to the internal wall of the photobioreactor tube, thus preventing light penetration into the tube and reducing bioreactor productivity. Robust methods for controlling wall growth are needed. Wall growth is controlled by some of the following methods:

1. Use of large slugs of air to intermittently scour the internal surface of the tube.
2. Circulation of close fitting balls in continuous run tubes to clean the internal surface.
3. Highly turbulent flow.
4. Suspended sand or grit particles to abrade any biomass adhering to the internal surface. Potentially, enzymes that digest the polymer glue that binds algal cells to the tube walls, may be used for controlling wall growth.

Bioprocess intensification approaches that have proved so successful in improving the economics of various biotechnology-based processes have been barely assessed for use with photobioreactors.

Thus as discussed here, microalgal biodiesel is technically feasible. It is the only renewable biodiesel that can potentially completely displace liquid fuels derived from petroleum. Economics of producing microalgal biodiesel need to improve substantially to make it competitive with petrodiesel, but the level of improvement necessary appears to be attainable.

Producing low-cost microalgal biodiesel requires primarily improvements to algal biology through genetic and metabolic engineering. Use of the biorefinery concept and advances in photobioreactor engineering will further lower the cost of production. In view of their much greater productivity than raceways, tubular photobioreactors are likely to be used in producing much of the microalgal biomass required for making biodiesel.

Photobioreactors provide a controlled environment that can be tailored to the specific demands of highly productive microalgae to attain a consistently good annual yield of oil.

## *Utilisation of by-products*

The cost of biodiesel production can be reduced by proper utilisation of by-products such as glycerol and meal cake apart from improving transesterification process. Glycerol from biodiesel contain some peculiar impurities and may not be suitable to process according to the usual technologies to produce pharmaceutical or top grade product.

There is a need not only to develop purification technology for glycerol but also for its utilisation as a raw material for the production of other chemicals as large quantity (0.2 MMT/A) of the glycerol will be available even if 5 per cent diesel is targeted to be replaced by biodiesel against the present glycerol demand in Indian which is the tune of 0.04 MMT/A.

There is a need to find the use of meal cake which will be available in large quantities to reduce the cost of biodiesel. Meal cake may be used as fertiliser, as cattle feed after detoxification, etc.

## *Utilisation as fuel*

*Biodiesel characterization:* In India most of the trials have been carried out using biodiesel from feed stocks like Jatropha curcas and Karanj oils. Biodiesel from different feedstocks even after meeting ASTM standards may vary in composition, lubricity, oxidation stability, etc. It is desirable to carry out tests on biodiesel from all possible feed stocks available in India and generate comparative data on fuel composition.

*Compatibility with additives:* Biodiesel may have different response with present day additives. There is a need to study in detail the response of different available additives, their dosages on the biodiesel, e.g.

1. Biodiesel thickens at low temperature so it needs cold flow improver additives with acceptable CFPP.
2. Pour point depressants commonly used for diesel may not work for biodiesel.
3. Poor oxidation stability of biodiesel may require increased amount of stabiliser.
4. To avoid growth of algae in presence of water, some biocide may be needed.

Some newer additives may have to be developed/required for biodiesel.

Compatibility with elastomers: Though biodiesel (B100) can be used as a replacement of petroleum diesel, further study is needed to study the effect of biodiesel on elastomers, additive response, corrosion, etc. Minor modifications in the engine may also be required.

*Stability of biodiesel:* Biodiesel ages more quickly than fossil diesel fuel due to the chemical structure of fatty acid esters present in biodiesel. There are three types of stability criteria, which need to be studied: (i) oxidation stability, (ii) thermal stability, and (iii) storage stability.

Poor oxidation and thermal stability can cause fuel thickening, formation of gum and sediments and may also affect engine oil due to dilution. Current knowledge and database is still inadequate. It is desirable to carry out tests on biodiesel from different feedstocks available in India and generate data in relation to fuel composition. Very little data is available on the long-term storage stability of biodiesel. Effect of presence of water, sediments, and additives on storage stability needs to be investigated in detail.

### *Engine performance*

No or very little data on effect of biodiesel from Jatropha and Karanj oil on emission and engine performance using various proportion of biodiesel is available. This needs validation on test engine beds. Apart from the study on engine performance on different capacities of engines/vehicles the following aspects need to be studied further:

1. Endurance tests for finding out wear on engine components like cylinder liner, piston rings, etc. analysis for carbon deposit on piston, value, injectors, etc.
2. Analysis of crankcase lubricating oil for assessing the deterioration or contamination due to blow by leakage.
3. Effect of additives to prevent gum formation need to be evaluated.

### *Toxicological studies*

Toxicological study is a prerequisite for introduction of any fuel. It is recommended that such studies in India should be initiated through concerned R&D centres such as ITRC, Lucknow.

## 22.12.7 Properties of biodiesel

A general understanding of the various properties of biodiesel is essential to study their implications in engine use, storage, handling and safety.

### *Density/Specific gravity*

Biodiesel is slightly heavier than conventional diesel fuel (specific gravity 0.88 compared to 0.84 for diesel fuel). This allows use of splash blending by adding biodiesel on top of diesel fuel for making biodiesel blends. Biodiesel should always be blended at top of diesel fuel. If biodiesel is first put at the bottom and then diesel fuel is added, it will not mix. Density control is specified in European specifications but not in ASTM specification. But for India it is proposed to keep density specifications to check for contamination/adulteration.

### *Cetane number*

Cetane number of a diesel engine fuel is indicative of its ignition characteristics. Higher the cetane number better it is in its ignition properties. Cetane number affects a number of engine performance parameters like combustion, stability, drivability, white smoke, noise and emissions of CO and HC. Biodiesel has higher cetane number than conventional diesel fuel. This results in higher combustion efficiency and smoother combustion. No correlation was found between the specific gravity and the cetane number of various biodiesel. It is important to note that Cetane Index, commonly used to indicate the ignition characteristics of diesel fuels, does not give correct results for biodiesel. Hence cetane index is not specified and a cetane number test is necessary. Even for a biodiesel blend, cetane index is not applicable as it does give a correct approximation of cetane number of the blend.

### *Viscosity*

In addition of lubrication of fuel injection system components, fuel viscosity controls the characteristics of the injection from the diesel injector (droplet size, spray characteristics, etc.). The viscosity of methyl esters can go to very high levels and hence, it is important to control it within an acceptable level to avoid negative impact on fuel injection system performance. Therefore, the viscosity specifications proposed are same as that of the diesel fuel.

### *Distillation characteristics*

The distillation characteristics of biodiesel are quite different from that of diesel fuel. Biodiesel does not contain any highly volatile components, the fuel evaporates only at higher temperature. This is the reason that sometimes sump lubrication oil dilution observed in many tests. The methyl esters present in biodiesel generally have molecular chains of 16–18 carbons which have very close boiling points. In other words, rather than showing a distillation characteristics, biodiesel exhibits a boiling point. Boiling point of biodiesel generally range from 330°C to 357°C. The limit of 360°C is specified mainly to ensure that high boiling point components are not present in biodiesel as adulterants/contaminants.

## *Flashpoint*

Flashpoint of a fuel is defined as the temperature at which it will ignite when exposed to a flame or spark. The flashpoint of biodiesel is higher than the petroleum-based diesel fuel. Flashpoint of biodiesel blends is dependent on the flashpoint of the base diesel fuel used, and increase with percentage of biodiesel in the blend. Thus in storage, biodiesel and its blends are safer than conventional diesel. The flashpoint of biodiesel is around 160°C, but it can reduce drastically if the alcohol used in manufacture of biodiesel is not removed properly. Residual alcohol in the biodiesel reduces its flashpoint drastically and is harmful to fuel pump, seals, elastomers, etc. It also reduces the combustion quality.

A minimum flashpoint for biodiesel is specified more from the point of view of restricting the alcohol content rather than a fire hazard. A minimum flashpoint of 100ºC is specified to ensure that excess methanol used for the esterification is removed. Another important consideration is that the test method used to find out flashpoint (ASTM D 93) gives high scatter in results at the flashpoint nears 100°C. Due to this reason, the ASTM D 6751 standard issued in Feb. 2002 calls for a flashpoint of min. 130°C though the intent is to get a min. value of 100°C.

## *Cold filter plugging point (CFPP)*

At low operating temperature fuel may thicken and not flow properly affecting the performance of fuel lines, fuel pumps and injectors. Cold filter plugging point of biodiesel reflects its cold weather performance. It defines the fuels limit of filterability. CFPP has better correlation than cloud point for biodiesel as well as diesel fuel. Biodiesel thicken at low temperatures so need cold flow improver additives to have acceptable CFPP.

## *Pour point*

Normally either pour point or CFPP are specified. French and Italian biodiesel specifications specify pour point whereas others specify CFFP. Since CFFP reflects more accurately the cold weather operation of fuel, it is proposed not to specify pour point for biodiesel. Pour point depressants commonly used for diesel fuel do not work for biodiesel.

## Cloud point

Cloud point is the temperature at which a cloud or haze of crystals appear in the fuel under test conditions and thus becomes important for low temperature operations. Biodiesel generally has higher cloud point than diesel fuel. Cloud point limit is not specified but ASTM D 6751 calls for reporting of the cloud point to alert the user of possible problem under cold climatic conditions.

## Aromatics

Biodiesel does not contain any aromatics so aromatic limits are not specified. It may be noted that conventional aromatic determination tests used for petroleum fuels does not give correct results for biodiesel, hence aromatics in a biodiesel blend can be determined only by testing the base diesel fuel before blending.

## Stability

Biodiesel age more quickly than fossil diesel fuel due to the chemical structure of fatty acids and methyl esters present in biodiesel. Typically there are up to 14 types of fatty acid methyl esters in the biodiesel. The individual proportion of presence of these esters in the fuel affects the final properties of biodiesel. Saturated fatty acid methyl esters (C14:0, C16:0, C16:0) increase cloud point, cetane number and improve stability whereas more polyunsaturates (C18:2, C18:3) reduce cloud point, cetane number and stability.

There are three types of stability criteria, which need to be studied:

1. Oxidation stability—more related to engine operation as engine components attain high temperatures during operation
2. Storage stability
3. Thermal stability

*Oxidation stability:* Poor oxidation stability can cause fuel thickening, formation of gums and sediments, which, in turn, can cause filter clogging and injector fouling. Iodine number indicates the tendency of a fuel to be unstable as it measures the presence of C=C bonds that are prone to oxidation. Generally instability increase by a factor of 1 for every C=C bond on the fatty acid chain. Thus, C18:3 are three times more unstable than C18:0 fatty acids oxidation stability of biodiesel varies greatly depending upon the feedstock used. In one study of 22 biodiesel samples taken from 7 European production sites, the induction period was found to vary from 1 hrs to 10 hrs.

*Thermal stability:* Current knowledge and database is still inadequate. More information is needed in this area.

*Storage stability:* Very little data is available on the long-term storage stability of biodiesel. Effect of presence of water, sediments, and additives on storage stability need to be investigated more. Based on the data available so far, it is recommended that biodiesel and its blends should not be stored in a storage tank or vehicle tank for more than 6 months. Depending upon the storage temperature and other conditions use of an appropriate antioxidants ( e.g. Tenox 21, t-butylhydroquinone, etc.) is suggested. The antioxidants must be properly mixed with the fuel for good effectiveness. To avoid growth of algae in fuel, water contamination need to be minimised and if necessary some biocide should be used. Currently not all of the biodiesel standards issued mention oxidation stability. Iodine number, viscosity and neutralisation number indirectly assesses it. Higher values are indicative of poor oxidation stability. Iodine number test does not pick up the stability additives if used. There is need to develop appropriate test methods for oxidation and storage stability of biodiesel. ASTM D 2274 is a good candidate test method.

### *Iodine number and polyunsaturated methyl ester (C 18:3+)*

In diesel engines, methyl esters have been known to cause engine oil dilution by the fuel. A high content of unsaturated fatty acids in the ester (indicated by high iodine number) increases the danger of polymerisation in the engine oil. Oil dilution decreases oil viscosity. Sudden increase in oil viscosity, as encountered in several engine tests, is attributed to oxidation and polymerisation of unsaturated fuel parts entering into oil through dilution. In saturated fatty acids all the carbon is bound to two hydrogen atoms by double bonds. More the double bonds the lower is the cloud point of oil. The tendency of the fuel to be unstable can be predicted by Iodine number. Different biodiesel have different stability performance.

When iodine is introduced in the oil, the iodine attaches itself over a single bond to form a double bond. Thus iodine number refer to the amount of iodine required to convert unsaturated oil into saturated oil. It does not refer to the amount of iodine in the oil but to the presence of unsaturated fatty acids in the fuel. ASTM D 1520 method for measurement of Iodine number does not recognise the presence of stability additive. Iodine number is not well suited to indicate the influence of methyl ester on engine. One value of iodine number can be obtained by using several grades of unsaturated acids. SO an additional parameter, linolenic acid (C18:3) content is specified and limited to 15 per cent in Austrian Standard ON C 1191.

### *Free and total glycerol*

The degree of conversion completeness of the vegetable oil is indicated by the amount of free and total glycerol present in the biodiesel. If the actual number is higher than the specified values, engine fouling, filter-clogging, etc.

can occur. Manufacturing process controls are necessary to ensure low free and total glycerine. Free glycerol if present can build up at the bottom of the storage and vehicle fuel tanks.

### *Mono-, di- and triglycerides*

Most of the biodiesel standards, except Austrian and ASTM, specify a maximum limit of 0.08 for mono-glyceride. Draft EU standard calls for same limit. Di- and triglycerides are also controlled in most of the standards. High levels of these glycerides can cause injector fouling, filter clogging, etc.

### *Ester content*

France (96.5 per cent), Italy (98 per cent) and Sweden (98 per cent) specify a minimum eater content whereas Austrian and ASTM Standards do not specify any limit.

### *Alkaline matter (Na, K)*

Alkaline matter is controlled mainly to ensure that the catalysts used in the esterification process are properly removed.

### *Total contamination*

Left over impurities at the time of manufacture (such as free proteins) may form solid particles and clog the fuel lines. Filtration and washing treatments at manufacturing level need to be robust.

### *Sulphur content*

Biodiesel generally contain less than 15 ppm sulphur. ASTM D 5453 test is a suitable test for such low level of sulphur. ASTM D 2622 used for sulphur determination of diesel fuels gives falsely high results when used for biodiesel. More work need to done to assess suitability of ASTM D 2622 application to B20 biodiesel blend. The increase in oxygen content of the fuel affects precision of this test method.

### *Lubricity*

Wear due to excessive friction resulting in shortened life of diesel fuel pumps and injectors, has sometimes ascribed to lack of lubricity in the fuel. Numerous premature breakdown and in some cases, catastrophic failures, have occurred failures. All diesel fuel injection equipment (fuel pump and injector) of the diesel engine have reliance on diesel fuels for its lubrication, especially the rotary (distributor) and common rail type systems. The lubrication of the pump is not provided by viscosity alone but also by the lubricity property of the fuel. Even when the viscosity of the fuel is correct, several parts of the pump can wear out due to lack of lubricity. The lubricity of the fuel depends on the crude source, refining process to reduce sulphur content and the type of additives used. Ball on cylinder lubricity evaluator (BOCLE) and high frequency reciprocating rig (HFFR) are commonly used for evaluating the lubricity of the fuel. BOCLE is normally used for finding the lubricity fuel without additive, as it does not properly characterise the lubricity of fuels with lubricity additives. HFFR method has been adopted by fuel injection manufactures for lubricity evaluation of diesel fuels and they recommend a limit of 460 microns wear scar diameter (WSD). Lower the WSD better is the lubricity of fuel. In case of BOCLE method a higher value is better.

Even with 2 per cent biodiesel mixed in diesel fuel, the WSD values comes down to around 325 micron and is sufficient to meet the lubricity requirements of the fuel injection pump (460 micron max.). B100 performs still better, with a WSD of about 314 micron. With further reduction of sulphur content is diesel for Euro II and Euro IV fuels, the lubricity loss due to sulphur removal can easily be compensated by the addition of appropriate amount of biodiesel in diesel fuel.

Two per cent inclusion into any conventional diesel fuel is sufficient to address the lubricity problem. It also eliminates the inherent variability associated with use of other additives to make fuel fully lubricious. Second the biodiesel is a fuel component itself—any addition of it does cause any adverse consequences. Since pure biodiesel has high lubricity, it is not specified in the specification. When biodiesel is used as lubricity blend (B2) or diesel fuel extender (B20), its lubricity characteristics has to meet the specification for the base fuel.

## *Sulphated ash*

Sulphated ash is controlled to ensure that all the catalysts used in the transesterification process are removed. Presence of ash can cause filter plugging and/or injector deposits. Soluble metallic soap, unremoved catalysts and other solids are possible sources of sulphated ash in the fuel.

Acid number/Neutralisation number

Acid number/neutralisation number is specified to ensure proper ageing properties of the fuel and/or a good manufacturing process. Acid number reflects the presence of free fatty acids or acids used in manufacture of biodiesel. It also reflects the degradation of biodiesel due to thermal effects. For example, during the injection process several times more fuel returns from the injector than that injected into the combustion chamber of the engine. The temperature of this return fuel can, sometimes, be as high as 90°C and thus accelerate the degradation of biodiesel. The resultant high acid number can cause damage to injector and also result in deposits in fuel system and affect life of pumps and filters. Sodium hydro peroxide and sulphuric acids are highly corrosive and can cause serious, many times permanent, injuries.

### *Water content*

Biodiesel and its blends are susceptible to growing microbes when water is present in fuel. The solvency properties of the biodiesel can cause microbial slime to detach and clog fuel filters.

### *Phosphorous content*

Phosphorous can come as impurity and can affect oxidation catalyst and cause injector fouling. As more and more OEMs are going to use catalytic converters in diesel engines, it is necessary to keep the level of phosphorous in fuel low. Usually biodiesel have less than 1 ppm phosphorus. The specification of minimum 10 ppm phosphorous content is intended to ensure compatibility with catalytic converters irrespective of the source of biodiesel.

### *Methanol/ethanol content*

High levels of free alcohol in biodiesel cause accelerated deterioration of natural rubber seals and gaskets. Damage to fuel pumps and injectors which have natural rubber diaphragms has been very common type of failure Methanol is membrane-permeable and can cause nerve damage. Therefore control of alcohol content is required.

### *Conradson carbon residue (CCR)*

Carbon residue of the fuel is indicative of carbon depositing tendencies of the fuel. Conradson carbon residue (CCR) for biodiesel is more important than that in diesel fuel because it show a high correlation with presence of free fatty acids, glycerides, soaps, polymers, higher unsaturated fatty acids, inorganic impurities and even on the additives used for pour point depression. Two methods are used to measure carbon residue:

1. 100 per cent residual.
2. 10 per cent residual.

Since most of the biodiesel boils at almost the same temperature it is difficult to get a 10 per cent residual upon distillation. Though the 10 per cent

CCR test is easier to do, more work need to be done before we use it in Indian specifications for biodiesel.

## 22.13 Specifications and quality standards

Standards are of vital importance for the producers, suppliers and users of biofuels. Government Authorities need approval standards for the evaluation of safety, risks and environmental protection. Standards are necessary for the approval and warrantee commitment for vehicles operated with biofuels and are therefore, a prerequisite for the market introduction and commercialisation of biofuels. Creation of standards shall help expand the market for renewable sources of energy in India.

Conventionally standards and codes for products have been developed, largely by examining the existing standards and codes in different countries and then writing standards for own country. With the formation of WTO, which seeks to eliminate discrimination of products based on national origin, and the realisation that, in future, biofuels like ethanol and biodiesel, can become internationally traded commodities like petroleum, it is essential that a worldwide view is taken while preparing a new national standard. But at the same time, the local imperatives (such as type of raw materials, etc.) must be given due consideration. In Europe biodiesel is predominantly made from rapeseed oil and most information and data available are dealing with the rapeseed methyl ester (RME). Most of the experience in Austria, Italy, is also on RME. Germany has developed a standard for fatty acid methyl ester. Most of the Irish experience is on use of tallow fat for manufacture of biodiesel. Very little experience is available on ethyl or propyl esters. No matter what the process or feedstock used, the biodiesel produced must meet rigorous specifications to be used as a fuel in a compression ignition engine. It is not possible to recognise any blanket superiority of one feedstock over other since feedstock does not reliably predict a fuel's final properties.

Knowing that fuel adulteration is very rampant in India it is important that we ensure that chemical- grade fatty acid methyl esters used for purposes such as detergent manufacture must not be allowed to use as engine fuel. A worldwide survey of biodiesel specification was done and an attempt was made to understand the rationale behind them before proposing a norm for India.

ASTM has issued biodiesel standard D 6751 in December 2001, which covers the use of pure biodiesel (B100) into conventional diesel fuel up to 20 per cent by volume (B20). This replaces the provisional specification PS 121 issued in 1999. Austria (ON C 1191), France (JO), Italy (UNI 10635) and Germany (DIN E 51606) had issued biodiesel standards in 1997, Sweden in

1996 and a common draft standard EN 14214 for the European Union has also been announced. The new Italian biodiesel standard, which will replace UNI 10635, has been finalised and will be released this year for public.

In India, we have lots of European Engine technologies, specially that for older engines. We have also adopted the European Emission Regulations. Moreover, compared to USA diesel engines are more popular in Europe. Europe has also done expensive work on biodiesel. Production of biodiesel in Europe is much ahead of that in USA. The result is the EN 14214 standard is more comprehensive than the ASTM standard. It is recommended that we adopt the EN 1421112 standard for India.

### 22.13.1 Engine warranties and biodiesel approval endorsements from engine manufacturers

Engines are designed, manufactured and warranted for a fuel that has certain specified properties. The engine manufacturers give warranty for material and workmanship of the products they make and typically recommend/define use of a fuel in their manuals. They do not warrant fuel of any kind. If there is a problem due to fuel, the fuel supplier must stand behind the customer. Therefore it is important to take endorsements from engine manufacturers for use of biodiesel and their blends.

Caterpillar and several other engine manufacturers recognise biodiesel meeting ASTM PS121, DIN 51606 Specifications. However, the stance taken by some manufactures is rather vague, such as caterpillar says 'it neither approves nor prohibits use of biodiesel in their engines'. For some of their engines, a blend of 5 per cent biodiesel with diesel fuel (B5) is approved. More than 5 per cent biodiesel in diesel fuel is not covered under engine warranty.

Several marine engine manufacturers of Japan, USA and Europe (like Mercuiser, Yanmar, etc.) endorse use of B100 as fuel. Some engine manufactures warranties the newer engines and insists on change of hoses, seals and rubber parts in their older engines. While other engine manufacturers give warranties on case-by-case basis. Most of the tractor companies in Europe and USA permit use of biodiesel in their engines.

### 22.13.2 Fuel quality test procedures

It is important to maintain the fuel quality within the fuel specification otherwise severe engine problems can occur. Two types of test procedures are necessary for ensuring good quality fuel to the customers:

1. Test procedures for production and supply quality of the biodiesel.
2. Quick test procedures to check the quality of the fuel in field.

In BIS meeting it was agreed to do field trials on biodiesel. It is recommended that these trials must investigate at least the effect of cetane number, distillation, specific gravity, aromatics, oxygen and cloud point of biodiesel and its blends.

### *Amount of biodiesel to be blended in diesel*

Use of biodiesel has been due to following factors:

1. Support to agriculture sector
2. Part replacement of imported crude
3. Emission benefit
4. Rural development program
5. Lubricity improver

If the main purpose of the use of biodiesel is emission benefits, then higher percentage of biodiesel is generally used. World over about 20–40 per cent biodiesel blends (B20, B40) have been used for getting appreciable emission benefits. However, this approach needs OEM's approvals as some rubber seals, etc. need changing for use of higher percentage of biodiesel. The lubricity benefits of using biodiesel, especially in ultra low sulphur diesel, can be obtained even at a very per cent addition, e.g. 0.5–1.0 per cent. For support to agriculture sector and for part replacement of imported crude the amount of biodiesel to be blended in diesel will depend upon:

1. Availability of biodiesel
2. Cost of biodiesel
3. Technical acceptability

### *Availability of raw material of desired quality*

For a national level biodiesel program availability of raw vegetable oil for conversion to biodiesel needs to be ensured. Presently, the oil is available in limited quantity and that to on seasonal basis. There is need to identify the oil seeds extractors and the parties working in the area of extraction of oils may be contacted.

### *Chemical treatment to produce biodiesel*

Vegetable oil once extracted from the seed need a chemical treatment called transesterification with lower alcohol (methanol or ethanol) in order to make fuel grade biodiesel. Presently this technology is available only at laboratory scale or at best on the bench scale. Though this chemical process is simple and well understood whoever there is a need to develop commercial scale plants. These plants could be integrated with oil extractions plants so as to reduce cost by sharing of utilities. Though both batch scale and continuous type plants are used world over, it may be better to start with batch type plants in order to reduce initial cost.

### *Testing of biodiesel*

Biodiesel produce must meet the specifications (ASTM D – 6751) in order to use it as a fuel component for transportation fuel. This specification requires elaborate testing and these tests can be done with the association of diesel marketing companies. It is recommended that some critical tests for example water content and acidity may be done at the plant level while the other test could be done at the centralised location.

### *Transportation of biodiesel to selected locations for blending*

Transportation of biodiesel does not require any special precautions and can be transported by tankers just as the diesel. In order to reduce the cost the initial introduction of biodiesel should be done at locations near to the production site.

### *Blending of biodiesel into diesel*

Blending at depot level may be a good solution for initial selective introduction of biodiesel at some locations. Biodiesel does not require any special storage or handling precautions whoever storage tanks and circulatory pumps for mixing need to be stationed at the blending site.

# 23
# Biohydrogen

## 23.1 Introduction

The term 'biohydrogen' means hydrogen produced via biological processes. The making of biohydrogen is different from that of biological hydrogen produced by algae.

Hydrogen gas is a high energy (122 kJ/g) clean fuel which can be used for many different purposes. Hydrogen can be produced by steam reforming of hydrocarbons and coal gasification. Hydrogen production from renewable resources by fermentation is a more promising method among the other alternatives. In accordance with sustainable development and waste minimisation issues, biological hydrogen production, known as 'green technology', has received considerable attention in recent years. Biohydrogen production can be realised by dark and light anaerobic fermentations. Hydrogen is produced as a by product in anaerobic digestion of organic wastes. In order to increase the amount of hydrogen production under anaerobic conditions, the activity of methanogenic bacteria should be reduced/inhibited, or the system should be operated under acidogenic conditions. Photosynthetic hydrogen production basically takes place by two pathways: (i) algae breaks down water to $H_2$ and $O_2$ in the presence of light energy, and (ii) photo-heterotrophic bacteria utilise organic acids such as acetic, lactic and butyric acid to produce $H_2$. The major advantages of the later method is more favourable process economy, reduced operating problems and higher rate of $H_2$ gas production. Organic acids produced in the acidogenic phase of anaerobic digestion of organic materials may be used as the substrate for production of hydrogen by the photo-heterotrophic organisms. Therefore, the hydrogen yield may be improved by using a two-stage process such as dark and photofermentations or by their combinations.

Sustainable production of hydrogen gas requires availability of sustainable raw materials such as renewable energy sources or biomass. Cellulose or starch containing biomass can be used as a reliable and renewable raw material for hydrogen gas production. A three step process scheme consisting of pre-treatment-hydrolysis, dark fermentation and photo-fermentation can be used for this purpose. The first step of pre-treatment includes grinding, acid hydrolysis, neutralisation and nutrient balancing to produce carbohydrate solution from the biomass. Fermentable sugars are converted to organic acids, $CO_2$ and hydrogen in the dark fermentation phase. Light-fermentation is used for production of hydrogen from organic acids under anaerobic conditions in the presence of light.

The major challenge in biohydrogen production by dark and light fermentation is to improve the rate and the yield of hydrogen production for an economic process. Biological and engineering studies must be concentrated on these issues. Raw material cost is another concern in biohydrogen fermentations. Therefore, waste materials and renewable resources such as biomass should be used for this purpose.

## 23.2 Production of biohydrogen

### 23.2.1 Biohydrogen by gasification

Besides production of biohydrogen from biogas, it can also be produced through gasification of biomass, similar to the production of bio-SNG. A gasification method has to be used that produces a gas with higher hydrogen content. Otherwise, additional steam reforming is needed to convert methane into hydrogen. Water gas shift is used to increase the hydrogen yield. Then the remaining $CO_2$ is removed by pressure swing adsorption or ceramic membrane separation, which leaves biohydrogen, which is to be used as an automotive fuel. In order to use it in this way, it has to be compressed or liquefied or stored in metal hydrides. Hydrogen can be used in either internal combustion engines or fuel cells. Since fuel cell vehicles are not commercially available yet and a distribution infrastructure for hydrogen cannot be realised in the short term, biohydrogen is considered a longer-term option for the transport sector. The main challenges for further development of biohydrogen are similar to those of other gasification-derived biofuels (except SNG).

Supercritical gasification, an option for the production of SNG, is also a useful technology for production of biohydrogen. However, in that case, steam reforming is necessary to convert the formed methane into hydrogen, which makes the process more expensive. Another option to produce hydrogen from wet biomass, which is also still at lab scale, is a technology called dark and photo fermentation. Hydrogen can be produced directly by anaerobic digestion (biogas). Dark fermentation is a similar process; however, it is manipulated in such a way that the desired end-product hydrogen is produced directly without the forming of methane, whereas hydrogen is normally an intermediate product in anaerobic digestion. During dark fermentation, besides hydrogen, organic acids are produced, which can be converted to hydrogen by a process called photo fermentation.

### 23.2.2 Biohydrogen by anaerobic codigestion of food waste and sewage sludge

Anaerobic codigestion of food waste and sewage sludge for hydrogen production was performed in serum bottles under various volatile solids (VS) concentrations (0.5–5.0 per cent) and mixing ratios of two substrates (0:100–100:0, VS basis). Through response surface methodology, empirical equations for hydrogen evolution were obtained. The specific hydrogen production potential of food waste was higher than that of sewage sludge. However, hydrogen production potential increased as sewage sludge composition increased up to 13–19 per cent at all the VS concentrations. The maximum specific hydrogen production potential of 122.9 ml/g carbohydrate-COD was found at the waste composition of 87:13 (food waste:sewage sludge) and the VS concentration of 3.0 per cent. The relationship between carbohydrate concentration, protein concentration, and hydrogen production potential indicated that enriched protein by adding sewage sludge might enhance hydrogen production potential. The maximum specific hydrogen production rate was 111.2 ml $H_2$/g VSS/hr. Food waste and sewage sludge were, therefore, considered as a suitable main substrate and a useful auxiliary substrate, respectively, for hydrogen production. The metabolic results indicated that the fermentation of organic matters was successfully achieved and the characteristics of the heat-treated seed sludge were similar to those of anaerobic spore-forming bacteria, Clostridium sp.

### 23.2.3 Milestones

In 1939 German researcher Hans Gaffron discovered, while working at the University of Chicago, algae can switch between producing oxygen and hydrogen.

1997—Professor Anastasios Melis discovered, after following Hans Gaffron's work, that the deprivation of sulphur will cause the algae to switch from producing oxygen to producing hydrogen. The enzyme, hydrogenase, he found was responsible for the reaction.

2006—Researchers from the University of Bielefeld and the University of Queensland have genetically changed the single-cell green alga *Chlamydomonas reinhardtii* in such a way that it produces an especially large amount of hydrogen. The Stm6 can, in the long run, produce five times the volume made by the wild form of alga and up to 1.6–2.0 per cent energy efficiency.

2007—It was discovered that if copper is added to block oxygen generation, algae will switch from the production of oxygen to hydrogen.

2007—Anastasios Melis studying solar-to-chemical energy conversion efficiency in *tlaX* mutants of *Chlamydomonas reinhardtii,* achieved 15 per cent efficiency, demonstrating that truncated Chl antenna size would minimise wasteful dissipation of sunlight by individual cells. This solar-to-chemical energy conversion process could be coupled to the production of a variety of biofuels including hydrogen.

2008—Anastasios Melis studying solar-to-chemical energy conversion efficiency in *tlaR* mutants of *Chlamydomonas reinhardtii,* achieved 25 per cent efficiency out of a theoretical maximum of 30 per cent.

Research: 2006—At the University of Karlsruhe, a prototype of a bioreactor containing 500–1000 litres of algae cultures is being developed. The reactor is to be used to prove the economic feasibility of the system in the next five years.

## 23.3 Hydrogen economy

The hydrogen economy is a proposal for the distribution of energy using hydrogen. Hydrogen ($H_2$) releases energy when it is combined with oxygen; however in practice, production of hydrogen from water requires more energy than is released when the hydrogen is used as fuel. Free hydrogen does not occur naturally, and thus it must be generated by electrolysis of water or another method. A reduction in carbon dioxide emission connected with hydrogen fuel is directly achieved only if the energy used to make hydrogen is obtained from noncarbon-based sources. Now-a-days the majority of hydrogen produced on earth comes from fossil fuels.

In the context of a hydrogen economy, hydrogen is thus an energy carrier, not a primary energy source. Nevertheless, controversy over the usefulness of a hydrogen economy has been raised by issues of energy sourcing, including fossil fuel use, climate change, and sustainable energy generation. Also, the net efficiency of hydrogen as an energy carrier is lower than currently used methods, and leads to more energy waste. Some futurists promote hydrogen as potential fuel for motive power (including cars and boats), the energy needs of buildings and portable electronics.

Proponents of a world-scale hydrogen economy argue that hydrogen can be an environmentally cleaner source of energy to end-users, particularly in transportation applications, without release of pollutants (such as particulate matter) or greenhouse gases at the point of end-use. A 2004 analysis asserted that ‘most of the hydrogen supply chain pathways would release significantly less carbon dioxide into the atmosphere than would gasoline used in hybrid electric vehicles' and that significant reductions in carbon dioxide emissions would be possible if carbon capture or carbon sequestration methods were utilised at the site of energy or hydrogen production.

Critics of a hydrogen economy point at the following facts:

1. Hydrogen is not freely available.
2. Hydrogen is a gas at most temperatures, and particularly difficult to handle.
3. Hydrogen is more dangerous than most substances; equipment owned by consumers would have to be checked periodically.
4. Hydrogen production requires resources, and ultimately leads to energy loss.

Hydrogen has been called the least efficient and most expensive possible replacement for gasoline (petrol) in terms of reducing greenhouse gases. A comprehensive study of hydrogen in transportation applications has found that 'there are major hurdles on the path to achieving the vision of the hydrogen economy; the path will not be simple or straightforward'. The Ford Motor Company has dropped its plans to develop hydrogen cars, stating that 'The next major step in Ford's plan is to increase over time the volume of electrified vehicles'.

Recent publicity describing the use of low cost materials and manufacturing processes challenge the popular critique. Hydrogen (renewable hydrogen) can be produced from renewable sources, thus enabling the intermittent and excess power generated to be stored for applications in transport, homes and businesses, thereby making off-grid wind and solar sources economic.

### 23.3.1 Rationale

A hydrogen economy is proposed to solve some of the negative effects of using hydrocarbon fuels in transportation, and other end-use applications where the carbon is released to the atmosphere. Modern interest in the hydrogen economy can generally be traced to a 1970 technical report by Lawrence W. Jones of the University of Michigan.

In the current hydrocarbon economy, the transportation of people and goods (so-called mobile applications) is fuelled primarily by petroleum, refined into gasoline and diesel, and natural gas. However, the burning of these hydrocarbon fuels causes the emission of greenhouse gases and other pollutants. Furthermore, the supply of hydrocarbon resources in the world is limited because of their inherent nature, and the demand for hydrocarbon fuels is increasing, particularly in China, India and other developing countries.

Hydrogen has a high energy density by weight. The fuel cell is also more technically but not economically efficient than an internal combustion engine. The hydrogen internal combustion engine is said to be about 38 per cent efficient, 8 per cent higher than gasoline internal combustion engine, while the fuel cell is 2–3 times more efficient than an internal combustion engine. However, the high capital cost of fuel cell, about $5,500/kW, is one of the major obstacles of its development that is needed to be overcome before commercialisation. Other technical obstacles of fuel cells include the purity requirement of hydrogen; with current technology, an operating fuel cell requires the purity of hydrogen to be as high as 99.999 per cent. On the other hand, hydrogen engine conversion technology is more economical than fuel cells.

### 23.3.2 Perspective: current hydrogen market (current hydrogen economy)

Hydrogen production is a large and growing industry. Globally, some 50 million metric tons of hydrogen, equal to about 170 million tons of oil equivalent, were produced in 2004. The growth rate is around 10 per cent per year. Within the United States, 2004 production was about 11 million metric tons (MMT), an average power flow of 48 gigawatts. (For comparison, the average electric production in 2003 was some 442 gigawatts.) As of 2005, the economic value of all hydrogen produced worldwide is about $135 billion per year.

There are two primary uses for hydrogen today. About half is used to produce ammonia ($NH_3$) via the Haber process, which is then used directly or indirectly as fertiliser. Because both the world population and the intensive agriculture used to support it are growing, ammonia demand is growing. The other half of current hydrogen production is used to convert heavy petroleum sources into lighter fractions suitable for use as fuels. This latter process is known as hydrocracking. Hydrocracking represents an even larger growth area, since rising oil prices encourage oil companies to extract poorer source material, such as tar sands and oil shale. The scale economies inherent in large scale oil refining and fertiliser manufacture make possible on-site production and 'captive' use. Smaller quantities of 'merchant' hydrogen are manufactured and delivered to end-users as well.

If energy for hydrogen production was available (from wind, solar or nuclear power), use of the substance for hydrocarbon synfuel production could expand captive use of hydrogen by a factor of 5 to 10. Present US use of hydrogen for hydrocracking is roughly 4 million metric tons per year (4 MMT/yr). It is estimated that 37.7 MMT/yr of hydrogen would be sufficient to convert enough domestic coal to liquid fuels to end US dependence on foreign oil importation, and less than half this figure to end dependence on Middle

East oil. Coal liquefaction would present significantly worse emissions of carbon dioxide than does the current system of burning fossil petroleum, but it would eliminate the political and economic vulnerabilities inherent in oil importation.

Currently, global hydrogen production is 48 per cent from natural gas, 30 per cent from oil, and 18 per cent from coal; water electrolysis accounts for only 4 per cent. The distribution of production reflects the effects of thermodynamic constraints on economic choices: of the four methods for obtaining hydrogen, partial combustion of natural gas in a NGCC (natural gas combined cycle) power plant offers the most efficient chemical pathway and the greatest off-take of usable heat energy.

The large market and sharply rising prices in fossil fuels have also stimulated great interest in alternate, cheaper means of hydrogen production. Currently, most hydrogen is produced on-site and the cost is approximately $0.32/lb and, if not produced on-site, the cost of liquid hydrogen is about $1.00/lb to $1.40/lb as in year 2007.

### 23.3.3 Production, storage and infrastructure

Today hydrogen is produced for merchant use and captive industrial applications using mature, thermodynamically efficient technologies. Linking its centralised production to a fleet of light-duty fuel cell vehicles will require the siting and construction of a distribution infrastructure with large investment of capital. Further, the technological challenge of providing safe, energy-dense storage of hydrogen on-board the vehicle must be overcome to provide sufficient range between fill-ups.

#### *Methods of production*

Hydrogen is industrially produced from steam reforming, which uses fossil fuels such as natural gas, oil or coal. The energy content of the produced hydrogen is less than the energy content of the original fuel, some of it being lost as excessive heat during production.

Additionally, steam reforming leads to carbon dioxide emissions, in the same way as a car engine would do. A small part (4 per cent in 2006) is produced by electrolysis.

Molecular hydrogen is not available on earth in convenient natural reservoirs, though it is an atmospheric trace gas having a mixing ratio of 500 parts per billion by volume in addition to being produced by microbes and consumed by methanogens in a rapid biological hydrogen cycle. Most molecular hydrogen in the lithosphere is bonded to oxygen in water. Hydrogen is presently most economically produced using fossil fuels. In practice this is usually methane, though hydrogen can also be produced via steam reforming or partial oxidation of coal and fossil fuels. It can also be produced via electrolysis using electricity and water, consuming approximately 50 kWh of electricity per kilogram of hydrogen produced. Though the use of platinum as a catalyst for electrolytic separation of $H_2O$ into hydrogen and oxygen is well-known, some companies have now found ways to make fuel cells without platinum; unfortunately this new process makes use of other rare and expensive metals. Nuclear power can provide the energy for hydrogen production by a variety of means, but its wide scale deployment is opposed in some Western economies while it is embraced in others. Renewable energy is being used to produce hydrogen in Denmark and Iceland.

The environmental effects of hydrogen production can be compared with alternatives, taking into account not only the emissions and efficiency of the hydrogen production process but also the efficiency of the hydrogen conversion to electricity in a fuel cell.

While hydrogen (the element) is abundant on earth, and indeed is the most abundant element in the universe, manufacturing hydrogen does require the consumption of a hydrogen carrier such as a fossil fuel or water. The former consumes the fossil resource and produces carbon dioxide, but often requires no further energy input beyond the fossil fuel. Decomposing water requires electrical or heat input, generated from some primary energy source (fossil fuel, nuclear power or a renewable energy).

### *Kvaerner-process*

The Kvaerner-process or Kvaerner carbon black and hydrogen process (CB&H) is a method, developed in the 1980s by a Norwegian company of the same name, for the production of hydrogen from hydrocarbons (CnHm), such as methane, natural gas and biogas.

Of the available energy of the feed, approximately 48 per cent is contained in the hydrogen, 40 per cent is contained in activated carbon and 10 per cent in superheated steam.

### *Fermentative hydrogen production*

Fermentative hydrogen production is the fermentative conversion of organic substrate to biohydrogen manifested by a diverse group bacteria using multienzyme systems involving three steps similar to anaerobic conversion. Dark fermentation reactions do not require light energy, so they are capable of constantly producing hydrogen from organic compounds throughout the day and night. Photofermentation differs from dark fermentation because it only proceeds in the presence of light. For example photofermentation with Rhodobacter sphaeroides $SH_2C$ can be employed to convert small molecular fatty acids into hydrogen. Electrohydrogenesis is used in microbial fuel cells where hydrogen is produced from organic matter while 0.2–0.8 V is applied.

### *Biological production*

Biological hydrogen can be produced in an algae bioreactor. In the late 1990s it was discovered that if the algae is deprived of sulphur it will switch from the production of oxygen, i.e. normal photosynthesis, to the production of hydrogen.

It seems that the production is now economically feasible by surpassing the 7–10 per cent energy efficiency (the conversion of sunlight into hydrogen) barrier.

Biological hydrogen can and is produced in bioreactors that utilise feedstocks other than algae, the most common feedstock being waste streams. The process involves bacteria feeding on hydrocarbons and exhaling hydrogen and $CO_2$. The $CO_2$ can be sequestered successfully by several methods, leaving hydrogen gas. A prototype hydrogen bioreactor using waste as a feedstock is in operation at Welch's grape juice factory in North East, Pennsylvania.

### *Electrolysis of water*

The predominant methods of hydrogen production rely on exothermic chemical reactions of fossil fuels to provide the energy needed to chemically convert feedstock into hydrogen. But when the energy supply is mechanical (hydropower or wind turbines), hydrogen can be made via high pressure electrolysis or low pressure electrolysis of water. In current market conditions, the 50 kWh of electricity consumed to manufacture one kilogram of compressed hydrogen is roughly as valuable as the hydrogen produced, assuming 8 cents/kWh. The price equivalence, despite the inefficiencies of electrical production and electrolysis, is due to the fact that most hydrogen is made from fossil fuels which couple more efficiently to producing the chemical directly, than they do to producing electricity. However, this is of no help to a hydrogen economy, which must derive hydrogen from sources other than the fossil fuels it is intended to replace.

### *High-pressure electrolysis*

High pressure electrolysis is the electrolysis of water by decomposition of water ($H_2O$) into oxygen ($O_2$) and hydrogen gas ($H_2$) by means of an electric current being passed through the water. The difference with a standard electrolyser is the compressed hydrogen output around 120–200 Bar (1740–2900 psi). By pressurising the hydrogen in the electrolyser the need for an external hydrogen compressor is eliminated, the average energy consumption for internal compression is around 3 per cent.

### *High-temperature electrolysis*

Hydrogen can be generated from energy supplied in the form of heat (e.g. that of concentrating solar thermal or nuclear) and electricity through high-temperature electrolysis (HTE). In contrast with low-temperature electrolysis, HTE of water converts more of the initial heat energy into chemical energy (hydrogen), potentially doubling efficiency, to about 50 per cent. Because some of the energy in HTE is supplied in the form of heat, less of the energy must be converted twice (from heat to electricity, and then to chemical form), and so potentially far less energy is required per kilogram of hydrogen produced.

### *Nuclear*

One side benefit of a nuclear reactor that produces both electricity and hydrogen is that it can shift production between the two. For instance, the plant might produce electricity during the day and hydrogen at night, matching its electrical generation profile to the daily variation in demand, and off loading the extra output at night into a storable medium for energy. It is possible that research into HTE and high-temperature nuclear reactors may eventually lead to a hydrogen supply that is cost-competitive with natural gas steam reforming.

For example, some prototype generation IV reactors have coolant exit temperatures of 850–1000°C, considerably hotter than existing commercial nuclear power plants. High temperature (950–1000°C) gas cooled nuclear reactors have the potential to split hydrogen from water by thermochemical means using nuclear heat.

General atomics predicts that hydrogen produced in a high temperature gas cooled reactor (HTGR) would cost $1.53/kg. In 2003, steam reforming of natural gas yielded hydrogen at $1.40/kg. At 2005 natural gas prices, hydrogen costs $2.70/kg. HTE has been demonstrated in a laboratory, at 108 megajoules (thermal) per kilogram of hydrogen produced, but not at a commercial scale. The first commercial generation IV reactors are expected around 2030.

### *Concentrating solar thermal*

The high temperatures necessary to split water can be achieved through the use of concentrating solar power. Hydrosol–2 is a 100–kilowatt pilot plant at the Plataforma Solar de Almería in Spain which uses sunlight to obtain the required 800° to 1200°C to split water. Hydrosol II has been in operation since 2008. The design of this 100–kilowatt pilot plant is based on a modular concept. As a result, it may be possible that this technology could be readily scaled up to the megawatt range by multiplying the available reactor units and by connecting the plant to heliostat fields (fields of sun-tracking mirrors) of a suitable size.

## *Biocatalysed electrolysis*

Besides regular electrolysis, electrolysis using microbes is another possibility. Using microbial fuel cells, waste-water or plants such as can be used to generate power. Biocatalysed electrolysis should not be confused with biological hydrogen production, as the latter only uses algae and with the latter, the algae itself generates the hydrogen instantly, where with biocatalysed electrolysis, this happens after running through the microbial fuel cell and a variety of aquatic plants can be used. These include reed sweetgrass, cordgrass, rice, tomatoes, lupines, algae.

## *Thermochemical production*

There are more than 352 thermochemical cycles which can be used for water splitting, around a dozen of these cycles such as the iron oxide cycle, cerium(IV) oxide-cerium(III) oxide cycle, zinc and zinc-oxide cycle, sulphur-iodine cycle, copper-chlorine cycle and hybrid sulphur cycle are under research and in testing phase to produce hydrogen and oxygen from water and heat without using electricity. These processes can be more efficient than high-temperature electrolysis, typical in the range from 35–49 per cent LHV efficiency.

Thermochemical production of hydrogen using chemical energy from coal or natural gas is generally not considered, because the direct chemical path is more efficient.

None of the thermochemical hydrogen production processes have been demonstrated at production levels, although several have been demonstrated in laboratories.

## *Reactive production*

Hydrogen is the product of a number of chemical reactions with metals. Sodium is a classic example, with water and sodium metal reacting to form sodium hydroxide and hydrogen. Another example which has gained some recent interest is aluminium or an aluminium/gallium alloy reacting with water to produce aluminium hydroxide and hydrogen. In all cases the metal is consumed. The reaction product(s) (other than the hydrogen) would then be recovered for regeneration in an energy-consuming process or directly in some application.

## *Storage*

Although molecular hydrogen has very high energy density on a mass basis, partly because of its low molecular weight, as a gas at ambient conditions it has very low energy density by volume. If it is to be used as fuel stored on board the vehicle, pure hydrogen gas must be pressurised or liquefied to provide sufficient driving range. Increasing gas pressure improves the energy density by volume, making for smaller, but not lighter container tanks. Achieving higher pressures necessitates greater use of external energy to power the compression. Alternatively, higher volumetric energy density liquid hydrogen or slush hydrogen may be used. However, liquid hydrogen is cryogenic and boils at 20.268 K (–252.882°C or –423.188°F). Cryogenic storage cuts weight but requires large liquefaction energies. The liquefaction process, involving pressurising and cooling steps, is energy intensive. The liquefied hydrogen has lower energy density by volume than gasoline by approximately a factor of four, because of the low density of liquid hydrogen—there is actually more hydrogen in a litre of gasoline (116 grams) than there is in a litre of pure liquid hydrogen (71 grams). Liquid hydrogen storage tanks must also be well insulated to minimise boil off. Ice may form around the tank and help corrode it further if the liquid hydrogen tank insulation fails.

The mass of the tanks needed for compressed hydrogen reduces the fuel economy of the vehicle. Because it is a small, energetic molecule, hydrogen tends to diffuse through any liner material intended to contain it, leading to the embrittlement or weakening, of its container.

Distinct from storing molecular hydrogen, hydrogen can be stored as a chemical hydride or in some other hydrogen-containing compound. Hydrogen gas is reacted with some other materials to produce the hydrogen storage material, which can be transported relatively easily. At the point of use the hydrogen storage material can be made to decompose, yielding hydrogen gas. As well as the mass and volume density problems associated with molecular hydrogen storage, current barriers to practical storage schemes stem from the high pressure and temperature conditions needed for hydride formation and hydrogen release. For many potential systems hydriding and dehydriding kinetics and heat management are also issues that need to be overcome.

### 23.3.4 Environmental concerns

The first concern is the origin of hydrogen. Hydrogen does not occur naturally; it has to be obtained from other sources, either by electrolysis of water or by fossil fuel reforming, the latter being commonest currently. This last process leads to an superior amount of carbon dioxyde, compared to using the fossil fuel directly in an internal combustion engine. The use of hydrogen hence leads to increase the carbon dioxide released.

The first process, electrolysis of water, requires electricity; in most countries, electricity is produced by burning coal, which again leads to increase the amounts of carbon dioxide.

Using renewable energies (such as solar or wind) to propel a generator, which would produce electricity, which would be used for water electrolysis, to produce hydrogen, which would be compressed and/or liquefied, to be transported over long distances, leads to a very low yield, hence a waste of resources.

Concern has also been raised to the by-products of hydrogen-nitrogen reactions in internal combustion engines. Air input into the combustion cylinder is approximately 78 per cent nitrogen, and the $N_2$ molecule has a binding energy of approximately 226 kilo calories per mole. The hydrogen reaction has sufficient energy to break this bond and produce unwanted components such as nitric acid ($HNO_3$), and hydrogen cyanide gas (HCN), both toxic by-products. Unbound nitrogen has been shown to produce nitrogen-oxygen compounds ($NO_x$) which have been shown to form tropospheric ozone through a photochemical reaction involving $NO_x$, volatile organic compounds (VOC) and sunlight.

There have also been some concerns over possible problems related to hydrogen gas leakage. Molecular hydrogen leaks slowly from most containment vessels. It has been hypothesised that if significant amounts of hydrogen gas ($H_2$) escape, hydrogen gas may, because of ultraviolet radiation, form free radicals (H) in the stratosphere. These free radicals would then be able to act as catalysts for ozone depletion. A large enough increase in stratospheric hydrogen from leaked $H_2$ could exacerbate the depletion process. However, the effect of these leakage problems may not be significant. The amount of hydrogen that leaks today is much lower (by a factor of 10–100) than the estimated 10–20 per cent figure conjectured by some researchers; for example, in Germany, the leakage rate is only 0.1 per cent (less than the natural gas leak rate of 0.7 per cent). At most, such leakage would likely be no more than 1–2 per cent even with widespread hydrogen use, using present technology.

### 23.3.5 Costs

When evaluating costs, oil and gas (fossil fuels) are generally used as the cheapest reference, even though the true cost of those fuels is seldom considered. Being fossil fuels—a non-renewable source of energy—the thousands of years required to be formed inside the earth seem to mean 'no cost' in most calculations and only the production costs are considered. Given such calculated low cost reference, any number of watts required for hydrogen production seem too much even if those watts come from a rather opposite—renewable—source of power like the Sun. Moreover, if a system for hydrogen generation and usage needs to compete with systems which use renewably generated electricity more directly, for example in trolleybuses or in battery electric vehicles, it will always be less efficient than them because of the low efficiency of multiple conversions.

From the above, hydrogen seems unlikely to be the cheapest carrier of energy over long distances.

Demonstrated advances in electrolyser and fuel cell technology by ITM Power are claimed to have made significant in-roads into addressing the cost of electrolysing water to make hydrogen, making cost effective production of hydrogen from off-grid renewable sources (compared to hydrocarbon fuels) possible for refuelling transport and applications for short range business and residential use.

Hydrogen pipelines are more expensive than even long-distance electric lines. Hydrogen is about three times bulkier in volume than natural gas for the same enthalpy, and hydrogen accelerates the cracking of steel (hydrogen embrittlement), which increases maintenance costs, leakage rates, and material costs. The difference in cost is likely to expand with newer technology: wires suspended in air can utilise higher voltage with only marginally increased material costs, but higher pressure pipes require proportionally more material.

Setting up a hydrogen economy would require huge investments in the infrastructure to store and distribute hydrogen to vehicles. In contrast, battery electric vehicles, which are already publicly available, would not necessitate immediate expansion of the existing infrastructure for electricity transmission and distribution, since much of the electricity currently being generated by power plants goes unused at night when the majority of electric vehicles would be recharged. A study conducted by the Pacific Northwest National Laboratory for the US Department of Energy in December 2006 found that the idle off-peak grid capacity in the US would be sufficient to power 84 per cent of all vehicles in the US if they all were immediately replaced with electric vehicles.

*Different production methods each have differing associated investment and marginal costs:* The energy and feedstock could originate from a multitude of sources i.e. natural gas, nuclear, solar, wind, biomass, coal, other fossil fuels, and geothermal.

### *Natural gas at small scale*

Uses steam reformation. Requires 15.9 million cubic feet (4,50,000 $m^3$) of gas, which, if produced by small 500 kg/day reformers at the point of dispensing (i.e., the filling station), would equate to 7,77,000 reformers costing $1 trillion dollars and producing 150 million tons of hydrogen gas annually. Obviates the need for distribution infrastructure dedicated to hydrogen; $3.00 per GGE (Gallons of gasoline equivalent).

### *Nuclear*

Provides energy for electrolysis of water. Would require 240,000 tons of unenriched uranium—that's 2000, 600 MW power plants, which would cost $840 billion or about $2.50 per GGE.

### *Solar*

Provides energy for electrolysis of water. Would require 2500 kWh of sun per square metre, 113 million 40 kW systems, which would cost $22 trillion or about $9.50 per GGE.

### *Wind*

Provides energy for electrolysis of water. At 7 metres per second average wind speed, it would require 1 million 2 MW wind turbines, which would cost $3 trillion dollars or about $3.00 per GGE.

### *Biomass*

Gasification plants would produce gas with steam reformation. 1.5 billion tons of dry biomass, 3300 plants which would require 113.4 million acres (4,60,000 $km^2$) of farm to produce the biomass. $565 billion dollars in cast or about $1.90 per GGE.

### *Coal*

FutureGen plants use coal gasification then steam reformation. Requires 1 billion tons of coal or about 1000, 275 MW plants with a cost of about $500 billion or about $1 per GGE.

## 23.3.6 Hydrogen production of greenhouse—neutral alcohol

This is one such artificial hydrocarbon-production plan. Hydrogen in a full 'hydrogen economy' was initially suggested as a way to make renewable energy in non-polluting form, available to automobiles which are not all-electric. However, a theoretical alternative to direct elemental hydrogen use in vehicles would address the same problem by using centrally produced hydrogen immediately, to make liquid fuels from a $CO_2$ source. Thus, hydrogen would be used captively to make fuel, and would not require expensive hydrogen transportation or storage. To be greenhouse-neutral, the source for $CO_2$ in such a plan would need to be formed air, biomass or from $CO_2$ which would otherwise be scheduled to be released into the air from non-carbon-capture fuel-burning power plants (of which there are likely to be many in the future, since economic carbon capture and storage is site-dependent and difficult to retrofit).

Captive hydrogen production to make more easily transportable and storable transportation fuels (such as alcohols or methane), using $CO_2$ input, can thus be seen as the artificial or 'non-biological green' analogue of biomass, biodiesel, and vegetable oil technologies. Green plants, in a sense, already use solar power to make captively produced hydrogen, which is then used to make easier-to-store-and-use fuels. In the plant leaf, solar energy is used to split water into hydrogen and oxygen, the latter gas being released. The hydrogen produced is then used 'on-site' by the plant to reduce $CO_2$ from the air into various fuels, such as the cellulose in wood, and the seed oils which are the basis for vegetable oil, biodiesel, etc. Hydrogen-produced alcohols would thus act as a very similar, but non-biological greenhouse-neutral way of producing energy stores and carriers from locally produced hydrogen (solar or otherwise). By not requiring hydrogen to be produced entirely by plant leaves, they would save cropland. The fuels, however, would be used for purposes of transportation exactly as in plans to use 'green fuels'. Rather than be transported from its production site, hydrogen in such plans would instead be used centrally and immediately, to produce renewable liquid fuels which may be cycled into the present transportation infrastructure directly, requiring almost no infrastructure change. Moreover, methanol fuel cells are beginning to be demonstrated, so methanol may eventually compete directly with hydrogen in the fuel cell and hybrid market.

## 23.3.7 Captive hydrogen synthetic methane production

In a similar way as with synthetic alcohol production, hydrogen can be used on-site to directly (nonbiologically) produce greenhouse-neutral gaseous fuels. Thus, captive-hydrogen-mediated production of greenhouse-neutral methane has been proposed (note that this is the reverse of the present method of acquiring hydrogen from natural methane, but one that does not require ultimate burning and release of fossil fuel carbon). Captive hydrogen (and carbon dioxide) may be used on-site to synthesise methane, using the Sabatier reaction. This process is about 80 per cent efficient, reducing the round trip efficiency to about 20 to 30 per cent, depending on the method of fuel utilisation. This is even lower than hydrogen, but the storage costs drop by at least a factor of three, because of methane's higher boiling point and higher energy density. Liquid methane has 3.2 times the energy density of liquid hydrogen and is easier to store. Additionally, the pipe infrastructure (natural gas pipelines) are already in place. Natural-gas-powered vehicles already exist, and are known to be easier to adapt from existing internal engine technology, than internal combustion autos running directly on hydrogen. Experience with natural gas powered vehicles shows that methane storage is inexpensive, once one has accepted the cost of conversion to store the fuel. However, the cost of alcohol storage is even lower, so this technology would need to produce methane at a considerable savings with regard to alcohol production. Ultimate mature prices of fuels in the competing technologies are not presently known, but both are expected to offer substantial infrastructural savings over attempts to transport and use hydrogen directly.

### 23.3.8 Hybrid strategy of electricity and synthetic methanol

Electricity can be more efficiently used in a storage battery than electrolysing water to hydrogen. For example, a storage battery may retain about 90 per cent of the electricity used to charge it, and be able to provide about 90 per cent of the electricity that it can store, resulting in a 'round trip' efficiency of about 81 per cent. This is compared with a 70 per cent efficiency of electrolysis and perhaps 60 per cent efficiency of a fuel cell, resulting in a round trip efficiency of only about 40 per cent for hydrogen—only about half the efficiency of batteries.

### 23.3.9 Electrical grid plus methanol fuel cells

Many of the hybrid strategies described above, using captive hydrogen to generate other more easily usable fuels, might be more effective than hydrogen-production alone. Short-term energy storage (meaning the energy is used not long after it has been captured) may be best accomplished with battery or even ultracapacitor storage. Longer term energy storage (meaning the energy is used weeks or months after capture) may be better done with synthetic methane or alcohols, which can be stored indefinitely at relatively low cost, and even used directly in some type of fuel cells, for electric vehicles. These strategies dovetail well with the recent interest in plug-in hybrid electric vehicles (PHEVs), which use a hybrid strategy of electrical and fuel storage for their energy needs. Hydrogen storage has been proposed by some to be optimal in a narrow range of energy storage time, probably somewhere between a few days and a few weeks. This range is subject to further narrowing with any improvements in battery technology. It is always possible that some kind of breakthrough in hydrogen storage or generation could occur, but this is unlikely given the physical and chemical limitations of the technical choices are fairly well understood.

# 24
# Algae fuel for future

## 24.1 Introduction

With the growing interest in regulating greenhouse gas emissions and declining fossil fuel reserves, the technology of using algae for biofuel holds tremendous appeal. Recent breakthroughs in synthetic biology, closed-end loop photobioreactor systems, and raceway pond developments are helping to accelerate the advancement of commercialisation of algae biofuels.

Algae are a large and diverse group of simple, typically autotrophic organisms, ranging from unicellular to multicellular forms. They are amongst the oldest plant organisms to have inhabited the world. Fossilised remains of this plant group became known from the Cambrian Age. Recent interest among researchers and industrialists in algae as one of the most promising sources for biodiesel production has emerged due to the following reasons: unlike corn, algae are not food crops and hence they can be grown away from farms and forests, minimising damages caused to eco and food chain systems. They are harvested quickly, dramatically speeding up the production process. They can be also grown in sewage and next to power-plant smokestacks where they digest pollutants to produce oil. Thus, algae not only reduce a plant's global warming gases, but also consume other pollutants.

## 24.2 Source and resource

Like other plants, algae use photosynthesis to harness sunlight and carbon dioxide and energy is stored inside the cell as lipids (the source for oil) and carbohydrates. The properties that make them commercially attractive are: microalgae grow much faster than land grown plants, often 100 times faster. They can therefore be employed for production of biofuels in an economically effective and environmentally sustainable manner. Phototropic microalgae are being used increasingly as food and animal-feed additives, as a source of protein, vitamins, valuable metabolites and human-medicine preparations, in aqua-cultures, and in systems for the cleaning and regeneration of waste-water.

Algae-based technologies also provide a key medium to reduce greenhouse gas emissions from coal-fired power plants and other carbon intensive industrial processes. Driven by the increasing concerns on global climate change, companies have started examining different forms of algae as a mode to reduce carbon emissions from power plants, generate renewable transportation fuels, and produce feed for fish and livestock. It is also believed that using algae would reduce the competition for other oil seeds, such as corn and soyabeans that are also used for food. In many ways, the cultivation of algae can be more environmental friendly than industrial farming. Depending on their species and environment, algae can grow at different rates and produce 30 to 70 per cent lipids per cell. Among biofuel projects, algae are commonly grown either in ponds or in translucent containers, called photobioreactors. In both cases the growth of algae requires a source of carbon, light, nutrients, and warm water. In any algae-based oil production system, the algae are harvested from growing process in the form of algae paste. It is then dewatered either by heat drying or dewatering presses. The algae paste can also be dewatered using centrifuges. Oil is then separated from the paste by a chemical process or by pressing in a high pressure device such as a screw press. The finished product is algae oil (Fig. 24.1) in a form suitable for use in the transesterification process to make biodiesel fuel.

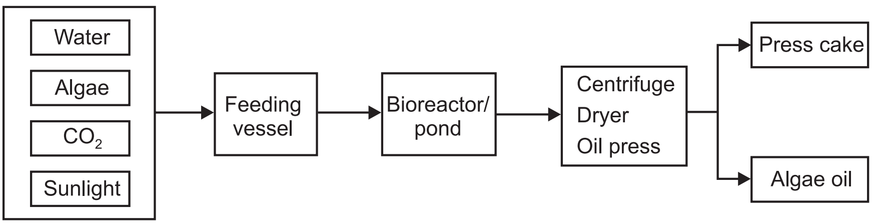



**Figure 24.1** Pictorial process showing the production of algae oil

## 24.3 Microalgae farming

The economy of microalgae production depends on the technology employed for their harvesting and the concentration of the algal suspension to obtain a product to sell or for further processing. The choice of harvesting methods depends on factors, viz. (i) type of algae that has to be harvested (filamentous, unicellular, etc.), (ii) whether harvesting occurs continuously or batch wise, (iii) energy demand per cubic metre of algal suspension, and (iv) investment costs. Different technologies, including chemical flocculation, biological flocculation, filtration, centrifugation and ultrasonic aggregation have been investigated for microalgal biomass harvesting. Harvesting is done after the algae in PBR or pond reaches its maximum density. The harvesting method depends on the species, cell density and on culture conditions. The main problem with harvesting lies in the small sizes (diameter of 3–50 μm) of algal cells. Also, when the culture is removed from the photobioreactor, it is usually present in very dilute concentrations (less than 0.5 g·l–1).

Thus, large volumes must be handled. Basically, harvesting involves solid-liquid separation processes that can be classified into two kinds of separation: (i) the liquid is constrained in a vessel and particles can move freely within liquid, e.g. sedimentation (gravity and centrifugal) and flotation; (ii) the particles are constrained by a permeable medium through which liquid can flow, e.g. filtration (cake and deep-bed) and screening. Few of them that can be employed for harvesting of algal biomass are summarised in Table 24.1.

A reasonable approach is to harvest the biomass in two steps. The first step is bulk harvesting, which is a large-scale operation with the aim of separating biomass from bulk algal suspension, leading to a concentration factor of 100 to 800 times. The second step is thickening, which further concentrates slurry by an additional 10 to 30 times. Existing technologies such as centrifugation and filtration are most commonly used for this purpose. Flocculation and flotation are widely used for the first step, bulk separation. The mechanism of flocculation involves neutralisation (pH 10–10.6 using NaOH) or reducing negative charge on micro algal cellular surface to aggregate cells in suspension, which can be achieved by adding flocculants (chemicals such as alum and ferric chloride/sulphate such as multivalent cations and cationic polymers, e.g. polyvinyl pyridinium, and chitosan). Another method, flotation, depends on trapping cells by dispersed micro-air bubbles. It is very attractive, as it does not require any addition of chemicals, resulting in a very clean sludge. However, at large scale flotation, engineering could be challenging.

**Table 24.1** Harvesting methods for algal biomass.

| Method | Advantages | Disadvantages |
|---|---|---|
| Centrifugation | Feasible for high value products/rapid large scale operations possible. Applicable for filamentous and non-filamentous microalgae. Biomass fully contained during recovery can harvest most microalgae species. | Spirulina is a problem as it floats during centrifugation. Energy intensive (3000 kWh/ton) expensive. |

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| Method | Advantages | Disadvantages |
|---|---|---|
| Filtration | Filtration from pond water usually clogs filters quickly. | Relatively slow process. Fails to recover bacterial-sized species. |
| Regular backwashing | Necessary that can increase cost for adequate removal. Effective for relatively large microalgae (e.g. spirulina). | |
| Gravity sedimentation | Good for low-value products DAF: Dissolved air flotation or electroflotation an alternative.. | Dilute biomass product. |
| Screening and straining | Filamentous organisms can be removed using screens of sieves. Very effective of spirulina. | Not very effective for unicellular organisms. |
| Flocculation/ Flotation (increases effective particle size) | Flocculants can be inexpensive, non-toxic, and effective at a low cone, e.g. bioflocculation. Only low level of mixing required. May only need pH adjustment. | Long processing period and decomposition of bioreactive product. Can be expensive and energy intensive if done on large scale. |
| Dehydration/ Thermal drying | Preserves the biomass. Spray drying used for high-value products. | Energy intensive and expensive. |

The type of harvesting employed depends heavily on the specific strain of organisms used in mass culture. Filtration, which operates under pressure or vacuum, is a preferred method for harvesting relatively large filamentous microalgae such as *Spirulina platensis*. For small cells of microalgae such as *Chlorella* and *Dunaliella,* conventional filtration is not practical, while membrane microfiltration and ultrafiltration are the possible alternatives. In case of gravity filtration, problem of clogging can be resolved by using vibrating screens which also increases the filtration rate. But cell rupturing might occur due to the cells rubbing against each other and filter. Therefore, with an increase in organic load in pond culture, possibility of bacterial contamination also increases. However, despite its various problems, filtering is currently the best method for optimal algal harvesting and concentration.

The last step in the production of the algal biomass is drying of the dewatered slurry to a moisture content of 12–15 per cent. Various methods of drying such as spray-drying, sun-drying, freeze-drying, fluidised bed drying, refractance window dehydration and vacuum-drying exist today. Dehydrating algae mass with a thin layer drum dryer yield is an excellent product from *Scenedesmus*. Drying algae on drum dryer has dual advantage of sterilising samples and breaking cell wall. An inexpensive and simple solar device can also be used for drying microalgal biomass with 90 per cent moisture content. Commercially, spray-drying is the most utilised drying method to produce pharmaceutical and food grade biomass. Despite the disadvantages of high capital and operational costs, the process is useful for obtaining a very pure and safe product.

Algae oils are extracted in a number of ways that varies from simple to complex. Many times depending on process of extraction, algae need not be dried before oil extraction. While the simplest of all is mechanical crushing, the choice of method depends on several factors such as the volume of oil to be extracted, requirement and investment limits. Many commercial manufacturers of vegetable oil (olive or corn oil) use a combination of mechanical pressing and chemical solvents in extracting oil.

## 24.4 Microalgae research and development

Tremendous commercial developments in this sector is taking place primarily all of them being at the very early stage of development or just a preliminary lab research. Some commercial interests (Table 24.2) into large scale algal-cultivation systems are looking to make joint venture into existing infrastructures, such as coal power plants or sewage treatment facilities. This approach not only provides raw materials for system, such as $CO_2$ and nutrients; but also changes those wastes into resources. The difficulties in efficient biodiesel production from algae lie in finding an algal strain with a high lipid content and fast growth rate that is not too difficult to harvest, and a cost-effective cultivation system (i.e. type of photobioreactor) that is best suited to that strain.

However, the idea to use algae in a fuel capacity was first tested about 50 years ago, when MIT, US scientists experimented with growing algae for biofuel. Thereafter, in the 1970s, the Department of Energy spent $3.3 million to establish its Aquatic Species Program (ASP), which was eventually shut down in 1996. The problem was finding a cost-effective way to grow algae on such a massive scale in the lab—like how to deliver just the right amount of light, among other things as well as a cheap method for extracting the oil. Using organic solvents or just squeezing the oil out of the algae is a pricey business.

**Table 24.2 Major organisations in the development of biofuel from algae.**

| Company/Institute | Remarks/ventures/objectives/developments |
|---|---|
| Algaelink, the Netherlands | Manufacturer of tubular photobioreactor utilised for algae development. Companies like KLM and some Chinese ventures are also involved. |
| Algenol biofuels, Baltimore, Maryland | It uses expensive refining processes by collecting ethanol vapours directly fromalgae to deliver billion gallons of cheap fuel a year. The company is backed by Sonora fields (north Mexico) S.A.P.I. de C.V. (a wholly owned subsidiary of Mexican owned biofields) to build $850 million project. BioFields paid over $100 million to license Algenol's technology. Its process absorbs about 90% of the $CO_2$ that is fed to the algae bioreactors, which are about 3 feet high and 50 feet long. Between 50% and 70% of the $CO_2$ goes into ethanol. The system can produce 6000 gallons of ethanol per acre per year. |
| Aquaflow Bionomic Corp., New Zealand | ABC is taking algae from Marlborough's sewage treatment ponds and using it to produce a biofuel that can be refined into biodiesel, aviation fuel and some of the chemicals used in the manufacture of plastics. The ponds cover an area of 60 hectares and are used to treat sewage from the 27,000 people in the area as well as municipal and agricultural waste. Using a technology from Honeywell (HON) subsidiary UOP has produced synthetic parafinic kerosene from sewage algae on a lab- and pilot plant-based scale. This fuelcan also be combined with conventional kerosene for jet-fuel. |
| Algo Dyne Ethanol Energy, US | Harvests biomass from marine algal blooms to produce carbon-neutral ethanol, methanol, biodiesel, electricity, coal and animal feed. |
| Aurora Biofuels, California, US | Developing algae to biodiesel with help of University of California, Berkeley. Raised a fresh fund of $20 million from Oak investment partners, Gabriel venture partner and Noventil. |
| Bayer technology services, Leverkusen GmbH, Germany | Deep-Dark-Tank (DDT) technology whereby algae grow on sugars from biomass (sugar, starch, cellulose), less capital than current PBR concepts, multi-feedstocks adaptable to seasonal variation. |
| Biofuel systems, Spain | BFS have developed an energy conversion process based on $CO_2$ that utilises three elements: Solar energy, photosynthesis and electromagnetic field. |
| Chevron and National Renewable Energy Laboratory (NREL), US | Agreement to investigation on production of liquid transportation fuels from algae. Invested $25 million from 1970 to 1990. Raised new fund from US DOE, Chevron and several other firms. |
| Colorado State University and Solix biofuels, US | Mass production cheap algae-derived oil for biodiesel. The algae are grown on unused land next to power and ethanol plants. |
| Columbia energy partners LLC, Washington, US | Biodiesel from algal oil generated by feeding algae carbon dioxide emissions from a coal fired power plant (600-MW facility). 7500 acres of open air algae ponds for commercial production will be given a try and Seattle-based BioAlgene LLC is providing the algae strains for this project. |

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| Company/Institute | Remarks/ventures/objectives/developments |
|---|---|
| Global green solutions (Vertigro algae technology) | AJV between GGS and Valcent Products has developed an environmentally friendly process algae are constantly circulated within clear plastic bio-reactors enhancing exposure to sunlight, $CO_2$ absorption and nutrient delivery. |
| Green star products, Montana, USA/Biotech Research Inc., Ensenada, Mexico | Daunting on technologies to convert biomass algae into usable fuels and products. Developed proprietary Hybrid algae production system (HAPS), a cross between an open and closed pond system. The prototype facility with an individual pond capacity of 40,000 litres. Has signed a contract to build 100-acre commercial algae facility with Biotech Research, Inc. a high tech research facility at the University of Baja California in Ensenada, Mexico. |
| Green fuels, Spain | Plans to produce 25,000 tons of algae for Aurantia SA, has invested $92 in finance. |
| International Energy, Inc., Vancouver, British Columbia | Working on biofuels derived directly from photosynthesis of green microalgae, which can accumulate up to 30% of their biomass in form of valuable biofuels. Additionally, raw algae can be processed to make biofuel, renewable equivalent of petroleum, and refined to make gasoline, diesel, jet fuel, and chemical feedstocks for plastics and drugs. |
| Origin oil Inc. California, US | Utilises a Helix BioReactor wherein low-energy lights are arranged in a helix pattern and a rotating vertical shaft design that allows algae culture to replicate exponentially within a smaller installation footprint. Developed a mechanised process of algae oil for biodiesel production, allowing greater control of the growth environment and efficient, low-cost industrial algae production. Employs cell rupture tech using an ultrasonic wave. Origin oil expects to soon scale up its experiments from a benchscale, eight gallon reactor, to a 200 gallon reactor. |
| Petrosun, China | Joint venture for algae-biofuel technology development between Shanghai Jun Ya Yan Technology and Petrosun USA. Received a $40 million fund from China. |
| PetroSun Biofuels, Arizona, US demonstration | Biodiesel facility from algae of 70,000 t/y capacity, pilot plant in Georgia. Company plans to supply 1,30,000 t/y to BioAlternatives, biodiesel plant in Louisiana. Targets to establish 1000 algal ponds in north Mexico to provide 6 million tons/y of algal oil. Algae Biofuels is another subsidiary of PetroSun Drilling, US. |
| Cellana, Royal Dutch Shell (Netherlands) and HR BioPetroleum (Hawaii) | Venture to build a pilot facility to grow marine algae and produce vegetable oil for conversion into biofuels. The island of Kona was identified for harvesting algae. 2.5 ha site facility is operational for 2 year and plan to extend to 1000 ha is overviewed. |
| Seambiotic, Israel/ Inventure Chemical, US | Primarily a organisation with a propriety technology of cultivating marine microalgae in open ponds utilising $CO_2$ emissions released directly from electric power plant's smoke stacks. Collaborated with Inventure Chemical Technology (ICT), US to convert biomass to bio-fuel including jet-fuel. ICT plans to sell the technology rather than selling algae itself. |

*Cont...*

| Company/Institute | Remarks/ventures/objectives/developments |
|---|---|
| Sandia Labs/ USDOE/Live fuels | Lab scale algae development to produce a range of advance biofuels, sites.located alongside coal-fired power plants to use $CO_2$. |
| Solazyme, SanFrancisco, US | A synthetic biology company unleashing power of aquatic microbes by growing its algae in fermentation tanks without sunlight, by feeding it sugar instead of light. $75 million investment in R&D finance from Chevron (a private investor). |
| Sapphire Energy, Las Cruces, California | Algae for biocrude and production of renewable gasoline. $100 million investment in R&D from Bill Gates Cascade Investment. |
| UK Carbon Trust | Announced $40 million grant for algae commercialisation by 2020. |

*Note:* Currently most of the companies are facing the downturn of market so plans might undergo a change.

Worldwide research into algae for mass-production of oil is mainly focused on microalgae; organisms capable of photosynthesis that are less than 2 mm in diameter, including diatoms and cyanobacteria; as opposed to macroalgae, e.g. seaweed. This preference towards microalgae is due largely to its less complex structure, fast growth rate, and high oil content (for example: *Botryococcus braunii, Cryptheco-dinium cohnii, Chlorella protothecoides, Dunaliella tertiolecta, Haematococcus pluvialis, Hantzschia Dl-160, Isochrysis galbana, Monallantus salina, Nitzschia palea, Nannochloris, Nannochloropsis, Nitzshia TR-114, Neochloris oleaabundans, Phaeodactylum tricontum, Pleurochrysis carterae, Scenedesmus TR-84, Stichococcus, Schizochytrium limacinum SR21, Scenedesmus dimorphus, Schizochytrium sp., Tetraselmis chuii, and Chlamidomonas reinhardtii*—the large scale genome projects have been completed for last organism).

Cultivating the right culture of algae requires adequate amount of light, heat and nutrients. Algae is becoming a preferred and much sought after feedstock for biodiesel, ethanol, petroleum and aviation companies seeking higher yield, lower cost, year-round fuel supplies.

Compared to the first generation agricultural crops that are grown seasonally, usually from food-based sources, algae is a sustainable source of biomass and can be produced and harvested three to four times a day continuously year round. The data presented in Table 24.3 illustrate the potential of algae oil as a feedstock for biodiesel.

## 24.5 Uses of microalgae

Algae are considered nutritious because of their high protein content and high concentrations of minerals, trace elements and vitamins. They provide food for people and livestock, serve as thickening agents in ice-cream and shampoo, and are used as drugs to ward off diseases. More than 150 species of algae are commercially important food sources, and over $2 billion of seaweed is consumed each year by human, mostly in Japan, China and Korea.

Table 24.3 Comparison of energy potential of terrestrial crops with microalgae.

| Feedstock | Biomass (mt/ha/y) | Oil content (% dry mass) | Biodiesel (mt/ha/y) | Energy content (BOE/1000 ha/day) |
|---|---|---|---|---|
| Soya | 1–2.5 | 20 | 0.2–0.5 | 3–8 |
| Rapeseed | 3 | 40 | 1.2 | 22 |
| Palm | 19 | 20 | 3.7 | 63 |
| Jatropha | 7.5–10 | 30–55 | 2.2–5.5 | 40–100 |
| Algae | 140–255 | 35–70 | 50–100 | 1150–2000 |

## 24.5 Uses of microalgae

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Harvesting algae on a large scale as a way of restoring bays and other shallow areas, an ecofriendly way of taking care of the algae can be seen. A broad range of valuable products can be harvested from the production of algal biomass. The utilisation areas of microalgae can be divided into three categories:

1. Energy, e.g. production of substances such as hydrocarbons, hydrogen, methanol, etc.
2. Foods and chemicals, e.g. proteins, oils and fats, sterols, carbohydrates, sugars, alcohols, etc.
3. Other chemicals, e.g. dyes, perfumes, vitamins/supplements, etc.

Many researchers have demonstrated that algal biomass can also be used as an effective feed substitute for animals. One type of microalgae, cyanobacteria or blue-green algae, has been studied extensively because of its valuable products. The edible species include *Nostoc, Spirulina,* and *Aphanizomenon,* which can be used as a raw, unprocessed food as they are rich in carotenoid, chlorophyll, phycocyanin, amino acids, minerals and bioactive compounds. Besides their nutritional value, these compounds have immense medicinal value, such as immune-stimulating, metabolism increasing, cholesterol reducing, anti-inflammatory and antioxidant properties.

The red alga *Porphyra,* called nori, is the most popular food product. After harvesting, it is dried, pressed into sheets, and used in soups, sauces, sushi, and condiments. Cyanobacteria species that are high in protein, such as *Spirulina,* are grown commercially in ponds and used mostly as a health food and cattle dietary supplement. Seaweeds are also applied to soils as a fertiliser and soil conditioner, as their high concentrations of potassium and trace elements improve crop production. Some species of cyanobacteria can turn atmospheric nitrogen into ammonia, a form that can then be used by plants as a nutrient. Farmers in tropical countries grow cyanobacteria in 'their flooded rice paddies to provide more nitrogen to the rice, increasing productivity as much as tenfold. Seaweeds are a critical source of three chemical extracts used extensively in the food, pharmaceutical, textile and cosmetic industries.

Brown algae yields alginic acid, which is used to stabilise emulsions and suspensions, is found in products such as syrup, ice cream and paint. Different species of red algae provide agar and carrageenan, which are used for the preparation of various gels used in scientific research. Bacteria, fungi and cell cultures in research experimentation are commonly grown on agar gels. Agar is also used in the food industry to stabilise pie fillings and preserve canned meat and fish. Carrageenan is also used as a thickening and stabilising agent in products such as puddings, syrups and shampoos.

Table 24.4 shows some commercially sold microalgal products paired with the species of microalgae that produces the goods. Another important aspect of microalgae is that they are rich in omega-3 fatty acids including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which have significant therapeutic importance inherent in the ability to act as an anti-inflammatory to treat heart disease. Furthermore, EPA has been shown to prevent and treat various medical conditions, such as coronary heart disease, blood platelet aggregation, abnormal cholesterol levels, several carcinomas, as well as arresting and minimising tumour growth.

**Table 24.4** Companies selling microalgal-based products.

| Company | Microalgae | Products |
|---|---|---|
| Cyanotech | *Spirulina pacifica* | Spirulina extracts nutritional supplements, immunological diagnostics, aquaculture feed/ pigments and food colouring |
| Cognis | *Dunaliella Salina* | Mixed carotenoids |
| Earthrise Nutritionals | *Spirulina sp.* | Nutritional supplement to inhibit replication and infectivity of viruses including HIV, CMV, HSV, and influenza A |

*Cont...*

*Cont...*

| Company | Microalgae | Products |
|---|---|---|
| Martek Biosciences Corporation | *Crypthecodinium cohnii* | Nutritional fatty acids |
| Mera Pharmaceuticals | *Haematococcus pluvialis* | Natural astaxanthin as a nutraceutical |
| NoriTech | *Porphyra* | Proteins, vitamins, minerals and nutritional fibres, nutraceuticals, anti-oxidant activity, treatment for anemia, helps reduce cholesterol |
| Nikken Sohonsha Corporation | *Chlorella sp.* *Dunaliella sp.* | Dietary supplements: polysaccharide N,β-1,3-glucan (Chlorella) and β-carotene (dunaliella) |
| Nature Beta Technologies | *Dunaliella bardowil* | β-carotene powder |
| PharmaMar | *Various* | Anticancer drugs derived from marine micro-organisms |
| Parrys Nutraceuticals | *Spirulina, Dunaliella salina, Haematococcus pluvialis* | Organic spirulina, natural mixed carotenoids, astaxanthin |
| Subitec GmbH | *Undisclosed* | Polyunsaturated acids |
| Solazyme | *Undisclosed* | No products yet brought to market |

Microalgae are the primary producers of omega-3 polyunsaturated fatty acids (PUFA) and fish usually obtain EPA via bioaccumulation in the food chain. In addition, algae can also be used as fertilisers, as raw material for the manufacture of paper and production of biogas. For agricultural purposes they can be used as soil improving matter in public parks and for certain salt tolerant crops such as white cabbage, beetroots and celery. But because of their relatively low content of phosphorus and nitrogen, algae cannot completely replace these substances but can be used in combination with other fertilisers. If used in large amounts, the algae's content of cadmium, nickel, chromium and lead may become a problem.

## 24.6 Miscellaneous uses

Algae can also be used in the production of biogas, paper and egg cartons. They can be used as a raw material for extraction of microcrystalline cellulose, which is used for the production of tablets in the pharmaceutical industry. Paper production works very well and there are good possibilities of using algae as a component in paper even on an industrial scale. However, problems in relation to storage, e.g. unpleasant smell and leakage of nutrients need to be solved. Recently, algae was surveyed for anticancer compounds with several cyanobacteria appearing to contain promising candidates. They can also serve as indicators of environmental problems in aquatic ecosystems. Because algae grow quickly and are sensitive to changing environmental conditions, they are often among the first organisms to respond to changes.

## 24.7 Perspectives

Research and development in algae production has been largely guided down three tracks—open and covered ponds, photobioreactors and fermenters with the first two being the most widely pursued. Algae hold great promise as a possible source of biodiesel. Growing algae is not hard but making it enough to be competitive with fossil fuel prices has eluded many companies and researchers betting on algae as a biofuel feedstock. The primary challenge is producing it on a large scale for which a generic model is yet to be designed.

While growing biodiesel algae, several factors must be considered, and different algae have different requirements as shown in Table 24.5.

**Table 24.5** Factors influencing algal growth.

| Factors | Remarks | Challenges ahead |
|---|---|---|
| Abiotic | Light (quality, quantity), photoinhibition | Isolate/select algal strains for mass cultures. |
| | Temperature | Maximise overall algal biomass productivity. |
| | Freshwater/marine | |
| | Nutrient concentration | Demonstrate large-scale, low cost algal cultivation. |
| | Oxygen, $H_2O$ | |
| | Carbon dioxide, sulphur dioxide and pH | Develop low cost harvesting technologies. |
| | Salinity, toxic chemicals | Photobioreactors limited to inoculums production. |
| | Pathogens (bacteria, fungi, and viruses) | Versatility of genetically modified strains. |
| Biotic | Competition by other algae | Large area required to absorb significant amount of $CO_2$. |

*Cont...*

*Cont...*

| Factors | Remarks | Challenges ahead |
|---|---|---|
| | Cell fragility/density; growth inhibition | Processing for biofuels and higher value coproducts. |
| | Reactor design/location/depth | Demonstrate waste treatment nutrient recovery. |
| | Single species or mixture | |
| Operational | Shear produced by mixing | |
| | Flow/dilution rate | |
| | Harvest frequency | |
| | Rate of nutrient addition | |

For instance: (i) water must be in a temperature range that will support specific algal species being grown and even then open ponds can become choked with invasive species, (ii) type of algal strain being used, (iii) nutrients must be controlled so that algae will not be 'starved', without wasting the nutrients, and (iv) algae need only l/10th the amount of light they receive from direct sunlight. In addition, process of cultivating algae requires huge amounts of water, which could limit where it is produced. With time and experience, algae cultivation might achieve dramatic improvements in density, growth rates and oil production. This requires improved growing methods, species selection, cultivation techniques, and bioengineering.

Moreover, price per kilogram of biomass is high on account of relatively large investments, costliness of pure $CO_2$, expensive mineral nutrients, low conversion efficiency in comparison with bacteria, seasonal purview of production, etc. This necessitates the search for technology optimisation. Extensive research is going on to identify few best strains for producing oil. Some of these pragmatic issues may have been initiated by various private companies, including oil industry giants Chevron and Shell, which are already researching algae fuel.

## 24.8 Algae fuel

Algae fuel, also called algal fuel, oilgae, algaeoleum and third-generation biofuel, is a biofuel from algae. High oil prices, competing demands between foods and other biofuel sources and the world food crisis have ignited interest in algaculture (farming algae) for making vegetable oil, biodiesel, bioethanol, biogasoline, biomethanol, biobutanol and other biofuels. Among algal fuels attractive characteristics: they do not affect freshwater resources, can be produced using ocean and waste-water, and are biodegradable and relatively harmless to the environment if spilled. Algae cost more per pound yet can yield over 30 times more energy per acre than other, second-generation biofuel crops. One biofuels company has claimed that algae can produce more oil in an area the size of a two car garage than a football field of soyabeans, because almost the entire algal organism can use sunlight to produce lipids, or oil. The United States Department of Energy estimates that if algae fuel replaced all the petroleum fuel in the United States, it would require 15,000 square miles (40,000 square kilometres), which is a few thousand square miles larger than Maryland. This is less than 1/7th the area of corn harvested in the United States in 2000.

The production of biofuels from algae is thought to help stabilise the concentration of carbon dioxide in the atmosphere at the present level rather than reducing it to a more 'healthy' level. During photosynthesis, algae and other photosynthetic organisms capture carbon dioxide and sunlight and convert it into oxygen and biomass. The rate at which this happens can be up to 99 per cent, which was shown by Weissman and Tillett in large-scale open-pond systems.

As of 2008, such fuels remain too expensive to replace other commercially available fuels, with the cost of various algae species typically between US$5–10 per kg. But several companies and government agencies are funding efforts to reduce capital and operating costs and make algae oil production commercially viable.

*Factors:* Dry algae factor is the percentage of algae cells in relation with the media where it is cultured, e.g. if the dry algae factor is 50 per cent, one would need 2 kg of wet algae (algae in the media) to get 1 kg of algae cells. Lipid factor is the percentage of vegoil in relation with the algae cells needed to get it, i.e. if the algae lipid factor is 40 per cent, one would need 2.5 kg of algae cells to get 1 kg of oil.

*Yield:* Yields (gallons of oil per acre per year) cover a vast range from 5000 to 1,50,000. If all aspects of the cultivation are controlled—temperature, $CO_2$ levels, sunlight and nutrients (including carbohydrates as a food source), then extremely high yields can be obtained. Such variation can make calculations on which to base 'fuel the world' scenarios very difficult.

For example, Glen Kertz of Valcent Products claims that 'algae can produce 1,00,000 gallons of oil per acre' per year. This relies on growing the algae in an entirely closed loop system. More recently, Valcent have claimed 1,50,000 gallons may be possible; their most recent actual reported yields were 33,000 gallons per acre per year. This amounts to 2,11,53,000 gallons per square mile per year. Thus, with the production capabilities of Valcent, it would only require 15,000 square miles (3.17E11gallons × 1 mi2/21,153,000 gallons) of land to completely displace petroleum use in the US. Current projections, however, do not take into account the energy losses due to converting the algae lipids into fuels.

## 24.9 Fuels

The vegoil algae product can then be harvested and converted into biodiesel; the algae's carbohydrate content can be fermented into bioethanol and biobutanol.

### 24.9.1 Extracting the oil

The extraction of oil from algae is one of the more costly processes, which determines the sustainability of algae-based biodiesel. Breakthroughs are anticipated to effectively extract oil from marine algae.

The breaking-down of algae cells to release oil, known as lysing, has long represented a challenge for the algae-to-oil industry. Algae cell walls are difficult to break down and while mechanical methods are energy-intensive, commonly used chemical solvents are toxic and require special handling.

Biomass residue from extraction can be used as protein animal feed; a source of other valuable microalgal products; or as a raw material for biogas production using anaerobic digestion.

The conventional methods of extraction are:

1. Oil expeller/press
2. Solvent extraction
3. Supercritical fluid extraction

More recent developments include:

1. Enzymatic extraction
2. Osmotic shock
3. Ultrasound assisted extraction

#### *Oil expeller/press*

Oil contained in dried algae is forced out under high mechanical pressure in an expeller or press. It utilises the same principle that is widely used in vegetable oil manufacturing. Large percentage of oil (70–75 per cent) can be extracted. A flow diagram of algal biorefinery concept is shown in Fig. 24.2. Press configurations include screw, expeller, piston type, etc. It is often used in conjunction with chemical extractions.

#### *Solvent extraction*

It is always used in combination with oil expeller/press as a pre-treatment stage. The combined process extracts more than 95 per cent of oil present in algae. Solvents used include hexane, benzene, petroleum distillates, ethers, etc. The disadvantages of the process are:

1. Toxicity of solvents and issues related to solvent residues in the cake and oil.
2. Explosion hazard, which requires stringent safety standard and higher cost in investment.

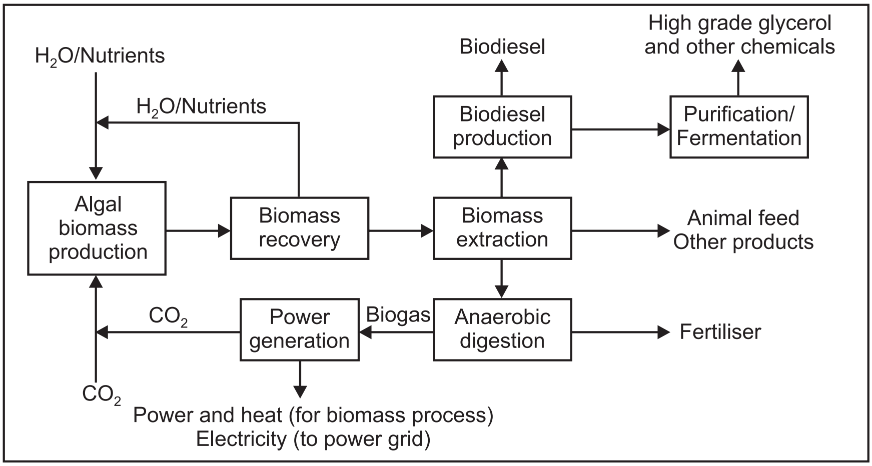


**Figure 24.2** Algal biorefinery concept

## *Supercritical fluid extraction*

$CO_2$ is liquefied under pressure and heated to critical point, the liquefied fluid then acts as the solvent in extracting the algae oil. The process extracts almost 100 per cent of the oils, but requires special equipment for containment and pressure. Water-based supercritical extraction processes have also been developed, as an alternative to $CO_2$-based processes and have the following advantages:

1. Low extraction times
2. Higher quality of the extracts
3. Lower costs of the extracting agent
4. Environmentally compatible
5. Extraction yield similar to conventional techniques

## *Enzymatic extraction*

Enzymatic extraction uses enzymes to degrade the cell walls with water acting as the solvent to facilitate the fractionation of the oil.

### *Osmotic shock*

Osmotic shock is a sudden reduction in osmotic pressure. This can cause cells in a solution to rupture. Single-celled organisms such as algae are more vulnerable to osmotic shock, and hence the process is considered a potential method to release oil from algae species.

### *Ultrasonic extraction*

The principle of ultrasonic extraction is based on acoustic cavitation effect when sound waves propagate through a liquid media with suitable vapour pressure and viscosity. The cavitation introduces strong shear force that easily ruptures the cell wall of algae, facilitating the extraction of oil content.

This is a safe and environmental friendly technology, which has minimum side effects due to its 'mild' extraction conditions. Efficiency and productivity can be easily enhanced in combination with other extraction techniques.

## 24.9.2 Algal biorefinery

A biorefinery is a facility that integrates a variety of conversion processes to produce multiple product streams. A biorefinery maximises the value derived from a biomass feedstock. For example, it can produce one or more low-volume, high-value chemical products; a low-value high-volume liquid transportation fuel; and electricity and process heat for its own use and/or export.

It has been identified as the most promising route to the creation of a sustainable bio-based economy. Feedstock costs remain the primary driver of competitive biodiesel production costs. While biodiesel economics have improved following the drop in palm oil pricing in 2008 (CPO prices plunged by over 65 per cent since March 2008), uncertainty continues to plague these markets and margins in the industry remain volatile, depending on commodity pricing and government policies.

## 24.9.3 Commercial developments

More than a 100 firms across the world are reported to be working on cultivation and harvesting of algal biomass. Some of these include: Algaen, arare, aquaflow, biodiesel, biofuels digest, biofuel review, bionavitas, carbon capture corp, cell tech, diversified energy, EnAgri, energy farms, energy update, ethanol India, genergetics, green energy, global green solutions, green shift, green start products, GS cleantech, infinifuel, inventure, Kent Sea Tech, Kiwikpower, OriginOil, PetroAlgae (XL TechGroup), plaatts, pelletbase, raytheon, texas clean fuels, simplexity and world oil (Table 24.6).

**Table 24.6** Current status of algae development.

| Company | Development |
|---|---|
| Live fuels | Seeking to produce fuel from bio-crude by 2010 |
| Green fuel technologies | Emissions to biofuels. Algae bioreactor fitted to fuels stacks |
| BFS (Spain) | Plankton to oil using solar energy, photosynthesis, electro-magnetics |
| Veridium | Bioreactors convert carbon dioxide from fermentation |
| DeBeers fuels (South Africa) | Partner with Green fuel. Targeting 16–24 billion litres by 2012 |
| Sapphire energy | Produced renewable gasoline in 2008; Targeting commercial production by 2012–13 |
| PetroSum | Arizona field testing in 2007, followed by refinery. Targeting 10 million gpy; Exploring other sites in Australasia and China |
| Solazyme | Algae fermentation and oil recovery processes; Detailed plant design completed |
| A2BE | Fully enclosed, bioisolated photobioreactors; Pilot plant expected to be operational by 2011 |

Thus, algae could play an important role as a potential feedstock for biofuels, as it offers significant advantages in terms of yield and productivity compared to conventional feedstocks. It may even have an advantage over other emerging 2nd generation technologies since it sequesters carbon in $CO_2$ emissions. It is able to utilise other pollutants such as $NO_2$, an added environmental advantage. However, its success will be dependent on advancements of current research and developments to commercialisation.

Algae could have a key biofuels role, but scale of its potential role remains uncertain and will be determined by the rate of advancement in technology and, most importantly, its economics. Factors and their relevance in microalgae is given in Table 24.7.

## 24.10 Integrated biodiesel production from microalgae

The key for large scale production of biofuels is to grow suitable biomass species in an integrated biomass production conversion system (IBPCS) at costs that enable the overall system to be operated at a profit. The illustration in Fig. 24.3 is a conceptual model for integrated biomass production that can be adopted for microalgal biodiesel production. The design of an IBPCS requires the combination and optimisation of several factors such as biomass culture, growth management, transport to conversion plants, drying, product separation, recycling, waste (liquid and solid) management, transport of saleable products and marketing. These factors can be simplified and reduced to three main groups; culturing of microalgae, harvesting and processing of biomass. In the idealised case, the conversion plants are located in or near the biomass growth areas to minimise the cost of transporting biomass to the plants, of which all the nonfuel effluents are recycled to the growth areas as demonstrated in Fig. 24.3.

**Table 24.7** Microalgae: A reality check.

| Factor | Relevance |
|---|---|
| Grow faster | Not all that relevant (except for R&D) |
| More productive | Possible, but not proven (need R&D) |
| Use power plant flue gas | $CO_2$—a need, not a virtue |
| Have high oil content | OK, but must be productive (R&D) |
| Use saline, brackish, waste-waters | Yes, use less water |
| Not compete with agriculture | OK, but we could eat algae! |
| Low cost of production/processing | Not true! |
| Closed photobioreactors can be used | Absolutely not true |
| Very large production potential | Many, many limitations |

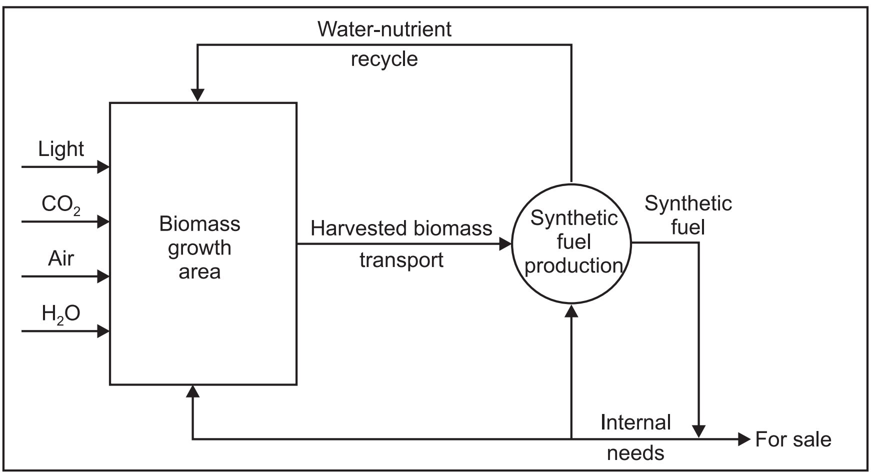


**Figure 24.3** A conceptual model for integrated biomass production and conversion integration system

The growth can be implemented in a microalgal farm. It would be equivalent to an isolated system with inputs of sunlight, air, $CO_2$, and water. Nutrients are replenished based on their status in the growth media and the environmental controls and waste disposal problems are minimised. Approximately, half of the dry weight of microalgal biomass is carbon, which is typically derived from $CO_2$. Thus, producing 1 kg of algal biomass fixes 1.6–1.8 kg of $CO_2$. The $CO_2$ must be fed continuously during daylight hours. Thus, an algae farm can be located adjacent to a power plant for utilising $CO_2$ from the combustion process. In such a circumstance, management of other gaseous emissions and waste-water by algal culture is also possible. It is because algae can remove effectively nitrogen, phosphorus, and heavy metals such as As, Cd, and Cr from aqueous solutions. Since emission control and waste-water management are costly and technically demanding, the use of waste-water as a source of nutrients for algae production, coupled with waste-water treatment are added environmental and economic benefits. The algal biomass produced needs to be further processed to recover the biomass. A problem associated with algal biomass is the relatively high water content. It normally requires pretreatments to reduce the water content and increase the energy density. This requirement consequently increases the energy cost. However, direct hydrothermal liquefaction in sub-critical water conditions can be employed to convert the wet biomass to liquid fuel without reducing the water content. Overall, by adopting integration approaches, such as waste-water treatment, nutrients and heavy metals recovery by algae culture, whereby additional economic benefits are created the obstacle of high cost of biodiesel production from algae may be overcome.

### 24.10.1 Production of microalgal biomass

The production of microalgal biodiesel requires large quantities of algal biomass. Most of algal species are obligate phototrophs and thus require light for their growth. Several cultivation technologies that are used for production microalgal biomass have been developed by researchers and commercial producers. The phototropic microalgae are most commonly grown in open ponds and photobioreactors. The open pond cultures are economically more favourable, but raise the issues of land use cost, water availability, and appropriate climatic conditions.

Further, there is the problem of contamination by fungi, bacteria and protozoa and competition by other microalgae. Photobioreactors offer a closed culture environment, which is protected from direct fallout, relatively safe from invading micro-organisms, where temperatures are controlled with an enhanced $CO_2$ fixation that is bubbled through culture medium. This technology is relatively expensive compared to the open ponds because of the infrastructure costs.

An ideal biomass production system should use the freely available sunlight. It is reported the best annual averaged productivity of open ponds was about 24 $g^{-1}$ dry weight $m^{-2}$ $d^{-1}$. A productivity of 100 $g^{-1}$ dry weight $m^{-2}$ $d^{-1}$ was achieved in simple 300 l culture systems. This level has been viewed as deriving from the light saturation effect.

The light requirement coupled with high extinction coefficient of chlorophyll in algae has necessitated the design and development of novel system for large scale growth. Experiments have also elucidated that algal biomass production can be boosted by the flashing light effect, namely by better matching photon input rate to the limiting steps of photosynthesis. Indeed, the best annual averaged productivity has been achieved in closed bioreactors. Tridici has reviewed mass production in photobioreactors. Many different designs of photobioreactor have been developed, but a tubular photobioreactor seems to be most satisfactory for producing algal biomass on the scale needed for biofuel production. Closed, controlled, indoor algal photobioreactors driven by artificial light are already economical for special high-value products such as pharmaceuticals, which can be combined with production of biodiesel to reduce the cost.

## Direct liquefaction of algae for biodiesel production

The microalgal biomass has relatively high water content (80–90 per cent) and this is major bottleneck for usage in energy supply. As most other virgin biomass, the high water content and inferior heat content makes the microalgal biomass difficult to be used for heat and power generation. Thus necessitating pretreatments to reduce water content and increase the energy density. As consequence the energy cost increases and makes the alternative less economically attractive.

Direct hydrothermal liquefaction in subcritical water conditions is a technology that can be employed to convert wet biomass material to liquid fuel. This technology is believed to mimic the natural geological processes thought to be involved in the formation of fossil fuel, but in the time scale of hours or even minutes. A number of technical terminologies have been used in the literature to refer to this technology, but it essentially utilise the high activity of water in subcritical conditions in order to decompose biomass materials down to shorter and smaller molecular materials with a higher energy density or more valuable chemicals.

Goudriaan claim the thermal efficiency (defined as the ratio of heating values of biocrude products and feedstock plus external heat input) for the hydrothermal upgrading process (HTU®) of biomass of a 10 kg dry weight $h^{-1}$ pilot plant is as high as 75 per cent. The main product of the process is bio-crude accounting for 45 per cent wt of the feedstock on dry ash free basis, with a lower heating value of 30–35 MJ $kg^{-1}$, which is compatible with fossil diesel and can be upgraded further. As moist biomass can be easily heated by microwave power, a process similar to the HTU® process using a novel microwave high-pressure (MHP) reactor has been developed in order to further minimise the energy consumption of the process.

In addition, integrated utilisation of high temperature and high pressure conditions in the process of hydrothermal liquefaction of wet biomass would significantly improve the overall thermal efficiency of the process. Suitable systems for such utilisation are an internal heat exchanger network or a combined heat and power (CHP) plant. A thermodynamic study, for example, has been performed to calculate the energy efficiency of the HTU process on the basis an integrated heat exchanger network.

Past research in the use of hydrothermal technology for direct liquefaction of biomass was very active. Only a few of them, however, used algal biomass as feedstock for the technology. Minowa report an oil yield of about 37 per cent (organic basis) by direct hydrothermal liquefaction at around 300°C and 10 MPa from *Dunaliella tertiolecta* with a moisture content of 78.4 wt%. The oil obtained at a reaction temperature of 340°C and holding time of 60 min. had a viscosity of 150–330 mPas and a calorific value of 36 kJ $g^{-1}$, comparable to those of fuel oil. The liquefaction technique was concluded to be a net energy producer from the energy balance. In a similar study on oil recovery from Botryococcus braunii, a maximum yield 64 per cent dry weight basis of oil was obtained by liquefaction at 300°C catalysed by sodium carbonate.

Also, Aresta have compared different conversion techniques, viz. supercritical $CO_2$, organic solvent extraction, pyrolysis, and hydrothermal technology for production of microalgal biodiesel. The hydrothermal liquefaction technique was more effective for extraction of microalgal biodiesel than using the supercritical carbon dioxide.

From these two studies, it is reasonable to believe that, among the selected techniques, the hydrothermal liquefaction is the most effective technological option for production of biodiesel from algae. Nevertheless, due to the level of limited information in the hydrothermal liquefaction of algae, more research in this area would be needed.

## 24.10.2 Other fuels from algae

### *Biobutanol*

Butanol fuel can be made from algae or diatoms using only a solar powered biorefinery. This fuel has an energy density similar to gasoline, and greater than that of either ethanol or methanol. In most gasoline engines, butanol can be used in place of gasoline with no modifications. In several tests, butanol consumption is similar to that of gasoline, and when blended with gasoline, provides better performance and corrosion resistance than that of ethanol or E85. The green waste left over from the algae oil extraction can be used to produce butanol.

### *Biogasoline*

Biogasoline is gasoline produced from biomass such as algae. Like traditionally produced gasoline, it contains between 6 (hexane) and 12 (dodecane) carbon atoms per molecule and can be used in internal-combustion engines.

### *Methane*

Through the use of algaculture grown organisms and cultures, various polymeric materials can be broken down into methane.

## 24.11 Straight vegetable oil (SVO)

The algal-oil feedstock that is used to produce biodiesel can also be used for fuel directly as 'straight vegetable oil' (SVO). The benefit of using the oil in this manner is that it does not require the additional energy needed for transesterification (processing the oil with an alcohol and a catalyst to produce biodiesel). The drawback is that it does require modifications to a normal diesel engine. Transesterified biodiesel can be run in an unmodified modern diesel engine, provided the engine is designed to use ultra-low sulphur diesel, which, as of 2006, is the new diesel fuel standard in the United States.

### 24.11.1 Hydrocracking to traditional transport fuels

Vegetable oil refining and green crude vegetable oil can be used as feedstock for an oil refinery where methods like hydrocracking or hydrogenation can be used to transform the vegetable oil into standard fuels like gasoline and diesel.

### 24.11.2 Jet fuel

Rising jet fuel prices are putting severe pressure on airline companies, creating an incentive for algal jet fuel research. The International Air Transport Association (IATA), for example, supports research, development and deployment of algal fuels. IATA's goal is for its members to be using 10 per cent alternative fuels by 2017.

On January 8, 2009, Continental Airlines ran the first test for the first flight of an algae-fueled jet. The test was done using a twin-engine commercial jet consuming a 50/50 blend of biofuel and normal aircraft fuel. It was the first flight by a US carrier to use an alternative fuel source on this specific type of aircraft. The flight from Houston's Bush International Airport completed a circuit over the Gulf of Mexico. The pilots on-board, executed a series of tests at 38,000 ft. (11.6 km), including a mid-flight engine shutdown. Larry Kellner, chief executive of Continental Airlines, said they had tested a drop-in fuel which meant that no modification to the engine was required. The fuel was praised for having a low flashpoint and sufficiently low freezing point, issues that have been problematic for other biofuels.

### 24.11.3 Algae cultivation

Algae can produce 15–300 times more oil per acre than conventional crops, such as rapeseed, palms, soyabeans or jatropha, and they have a harvesting cycle of 1–10 days, which permits several harvests in a very short time frame, increasing the total yield. Algae can also be grown on land that is not suitable for other established crops, for instance, arid land, land with excessively saline soil, and drought-stricken land. This minimises the issue of taking away pieces of land from the cultivation of food crops. They can grow 20 to 30 times faster than food crops.

Not only does algae produce biofuel, it also helps with reducing $CO_2$ emissions. Algae, like other fuels, releases carbon dioxide when it is burned. Fortunately, algae takes in $CO_2$ and replaces it with oxygen during the process of photosynthesis. Ultimately, its net emissions are zero because the $CO_2$ released in burning is the same amount that was absorbed initially. The hard part about algae production is growing the algae in a controlled way and harvesting it efficiently.

### 24.11.4 Photobioreactors

Most companies pursuing algae as a source of biofuels are pumping nutrient-laden water through plastic tubes (called bioreactors ) that are exposed to sunlight (and so-called photobioreactors or PBR). Running a PBR is more difficult than an open pond, and more costly.

Algae can also grow on marginal lands, such as in desert areas where the groundwater is saline, rather than utilise freshwater. The difficulties in efficient biodiesel production from algae lie in finding an algal strain with a high lipid content and fast growth rate that isn't too difficult to harvest, and a cost-effective cultivation system (i.e. type of photobioreactor) that is best suited to that strain. There is also a need to provide concentrated $CO_2$ to turbocharge the production.

### 24.11.5 Closed loop system

Another obstacle preventing widespread mass production of algae for biofuel production has been the equipment and structures needed to begin growing algae in large quantities. Maximum use of existing agriculture processes and hardware is the goal.

In a closed system (not exposed to open air) there is not the problem of contamination by other organisms blown in by the air. The problem for a closed system is finding a cheap source of sterile carbon dioxide ($CO_2$). Several experimenters have found the $CO_2$ from a smokestack works well for growing algae. To be economical, some experts think that algae farming for biofuels will have to be done next to power plants, where they can also help soak up the pollution.

### 24.11.6 Open pond

Open pond systems for the most part have been given up for the cultivation of algae with high-oil content. Many believe that a major flaw of the Aquatic Species Program was the decision to focus their efforts exclusively on open ponds; this makes the entire effort dependent upon the hardiness of the strain chosen, requiring it to be unnecessarily resilient in order to withstand wide swings in temperature and pH, and competition from invasive algae and bacteria. Open systems using a monoculture are also vulnerable to viral infection. The energy that a high-oil strain invests into the production of oil is energy that is not invested into the production of proteins or carbohydrates, usually resulting in the species being less hardy or having a slower growth rate. Algal species with a lower oil content, not having to divert their energies away from growth, have an easier time in the harsher conditions of an open system. Some open sewage ponds trial production has been done in Marlborough, New Zealand.

### 24.11.7 Nutrients

Nutrients like nitrogen (N), phosphorus (P), and potassium (K), are important for plant growth and are essential parts of fertiliser. Silica and iron, as well as several trace elements, may also be considered important marine nutrients as the lack of one can limit the growth of or productivity in an area. One company, green star products, announced their development of a micronutrient formula to increase the growth rate of algae. According to the company, its formula can increase the daily growth rate by 34 per cent and can double the amount of algae produced in one growth cycle.

## 24.11.8 Waste water

A possible nutrient source is waste-water from the treatment of sewage, agricultural or flood plain run-off, all currently major pollutants and health risks. However, this waste water cannot feed algae directly and must first be processed by bacteria, through anaerobic digestion. If waste-water is not processed before it reaches the algae, it will contaminate the algae in the reactor, and at the very least, kill much of the desired algae strain. In biogas facilities, organic waste is often converted to a mixture of carbon dioxide, methane, and organic fertiliser. Organic fertiliser that comes out of digester is liquid, and nearly suitable for algae growth, but it must first be cleaned and sterilised.

The utilisation of waste-water and ocean water instead of freshwater is strongly advocated due to the continuing depletion of freshwater resources. However, heavy metals, trace metals, and other contaminants in waste-water can decrease the ability of cells to produce lipids biosynthetically and also impact various other workings in the machinery of cells.

The same is true for ocean water, but the contaminants are found in different concentrations. Thus, agricultural-grade fertiliser is the preferred source of nutrients, but heavy metals are again a problem, especially for strains of algae that are susceptible to these metals. In open pond systems the use of strains of algae that can deal with high concentrations of heavy metals could prevent other organisms from infesting these systems.

At the Woods Hole Oceanographic Institution and the Harbour Branch Oceanographic Institution the waste-water from domestic and industrial sources contain rich organic compounds that are being used to accelerate the growth of algae. Also the Department of Biological and Agricultural Engineering of the University of Georgia is exploring microalgal biomass production using industrial waste-water.

Algaewheel, based in Indianapolis, Indiana, presented a proposal to build a facility in Cedar Lake, Indiana that uses algae to treat municipal waste-water and uses the sludge by-product to produce biofuel.

## 24.11.9 Investment

There is always uncertainty about the success of new products and investors have to consider carefully the proper energy sources in which to invest. A drop in fossil fuel oil prices might make consumers and therefore investors lose interest in renewable energy. Algal fuel companies are learning that investors have different expectations about returns and length of investments. AlgaePro Systems found in its talks with investors that while one wants at least 5 times the returns on their investment, others would only be willing to invest in a profitable operation over the long-term. Every investor has its own unique stipulations that are obstacles to further algae fuel development.

## 24.12 Biohydrogen

Biohydrogen is hydrogen produced via biological processes. Biohydrogen is not the same as biological hydrogen produced by algae.

### 24.12.1 Fermentation

Biohydrogen gas can be extracted from biomass through dark fermentation and/or photofermentation by bacteria.

#### *Fermentation plants*

Fermentative hydrogen production plants are proposed industrial plants for the production of hydrogen. They would typically involve processes such as thermophilic fermentation, dark fermentation and/or photofermentation and gas cleaning. Biohydrogen production can also involve an element of anaerobic digestion where the methane from biogas is converted through steam reforming into hydrogen. Biohydrogen produced from organic waste materials is a promising alternatives for sustainable energy sources. Hydrogen can be produced by bacterial species such as Rhodobacter sphaeroides and Enterobacter cloacae.

Biohydrogen is always and in no other way produced through dark fermentation either by mix culture of hydrogen producing sludge or pure culture of anaerobic bacteria such as Clostridium butyricum. Proton exchange membrane fuel cells (PEMFC) are the essential technology that made possible the conversion of the energy content in biohydrogen to electricity.

## 24.13 Biological hydrogen production

Biological hydrogen production is done in a closed photobioreactor based on the production of hydrogen by algae. Algae produce hydrogen under certain conditions. In 2000 it was discovered that if C. Reinhardtii algae are deprived of sulphur they will switch from the production of oxygen, as in normal photosynthesis, to the production of hydrogen.

### 24.13.1 Bioreactor design issues

1. Restriction of photosynthetic hydrogen production by accumulation of a proton gradient.

2. Competitive inhibition of photosynthetic hydrogen production by carbon dioxide.
3. Requirement for bicarbonate binding at photosystem II (PSII) for efficient photosynthetic activity.
4. Competitive drainage of electrons by oxygen in algal hydrogen production.
5. Economics must reach competitive price to other sources of energy and the economics are dependent on several parameters.
6. A major technical obstacle is the efficiency in converting solar energy into chemical energy stored in molecular hydrogen.

Attempts are in progress to solve these problems via bioengineering.

### 24.13.2 Truncated antenna

The chlorophyll (Chl) antenna size in green algae is minimised $H_2$or truncated, to maximise photobiological solar conversion efficiency and $H_2$ production. The truncated Chl antenna size minimises absorption and wasteful dissipation of sunlight by individual cells, resulting in better light utilisation efficiency and greater photosynthetic productivity by the green alga mass culture.

## 24.14 Algaculture

Algaculture is a form of aquaculture involving the farming of species of algae. The majority of algae that are intentionally cultivated fall into the category of microalgae (also referred to as phytoplankton, microphytes or planktonic algae). Macroalgae, commonly known as seaweed, also have many commercial and industrial uses, but due to their size and the specific requirements of the environment in which they need to grow, they do not lend themselves as readily to cultivation. Some of the commercial and industrial purposes of algae cultivation are for production of bioplastics, dyes and colorants, feedstock, pharmaceuticals, pollution control, algae fuel and for possible future food sources.

### 24.14.1 Oil extraction

Algae oils have a variety of commercial and industrial uses, and are extracted through a wide variety of methods.

### 24.14.2 Physical extraction

In the first step of extraction, the oil must be separated from the rest of the algae. The simplest method is mechanical crushing. When algae is dried it retains its oil content, which then can be ‘pressed’ out with an oil press. Many commercial manufacturers of vegetable oil use a combination of mechanical pressing and chemical solvents in extracting oil. Since different strains of algae vary widely in their physical attributes, various press configurations (screw, expeller, piston, etc.) work better for specific algae types. Often, mechanical crushing is used in conjunction with chemical solvents, as described below. Osmotic shock is a sudden reduction in osmotic pressure, this can cause cells in a solution to rupture. Osmotic shock is sometimes used to release cellular components, such as oil.

Ultrasonic extraction, a branch of sonochemistry, can greatly accelerate extraction processes. Using an ultrasonic reactor, ultrasonic waves are used to create cavitation bubbles in a solvent material. When these bubbles collapse near the cell walls, the resulting shock waves and liquid jets cause those cells walls to break and release their contents into a solvent. Ultrasonication can enhance basic enzymatic extraction. The combination 'sonoenzymatic treatment' accelerates extraction and increases yields.

### 24.14.3 Chemical extraction

Chemical solvents are often used in the extraction of the oils. The downside to using solvents for oil extraction are the dangers involved in working with the chemicals. Care must be taken to avoid exposure to vapours and skin contact, either of which can cause serious health damage. Chemical solvents also present an explosion hazard.

A common choice of chemical solvent is hexane, which is widely used in the food industry and is relatively inexpensive. Benzene and ether can also separate oil. Benzene is classified as a carcinogen.

Another method of chemical solvent extraction is Soxhlet extraction. In this method, oils from the algae are extracted through repeated washing or percolation, with an organic solvent such as hexane or petroleum ether, under reflux in a special glassware.

The value of this technique is that the solvent is reused for each cycle. Enzymatic extraction uses enzymes to degrade the cell walls with water acting as the solvent. This makes fractionation of the oil much easier. The costs of this extraction process are estimated to be much greater than hexane extraction. The enzymatic extraction can be supported by ultrasonication. The combination 'sonoenzymatic treatment' causes faster extraction and higher oil yields.

Supercritical $CO_2$ can also be used as a solvent. In this method, $CO_2$ is liquefied under pressure and heated to the point that it becomes supercritical (having properties of both a liquid and a gas), allowing it to act as a solvent. Other methods are still being developed, including ones to extract specific types of oils, such as those with a high production of long-chain highly unsaturated fatty acids.

## 24.15 Major breakthroughs in algae research

1. Two experimental facilities, the Oakridge national laboratory and the ASP Red Hawk Power Plant, have demonstrated very high yields using advanced photobioreactor-based designs. The Oakridge national laboratory yields 60 g $m^{-2}$ $d^{-1}$ of algae and the APS Red hawk power plant (green fuel's 3D matrix algae growth engineering scale unit, triangle airlift reactor) yields algae with an astounding average of 98 g $m^{-2}$ $d^{-1}$.
2. Current algal production systems fall between these ranges, i.e. Seambiotie Israel (currently at 20 g $m^{-2}$ at 8–40 per cent triacylglycerides (TAG), HR BioPetroleum Inc Hawaii (aims to achieve 50 g $m^{-2}$ day–l at 30 per cent TAG). A high-end closed bioreactor system that comprises world's largest closed photobioreactor in Klötze, near Wolfsburg, Germany, 700 $m^3$, are distributed in 500 km of tubes and produce up to 100 ton algae biomass per year.
3. A privately funded US $20 million program has engineered, built, and successfully operated a commercial-scale (2 Ha) modular production system coupling photobioreactors with open ponds in a two-stage process to produce *Haematococcus pluvialis* for an annual average rate of microbial oil production. This optimistic estimation was based on a photosynthetic efficiency of 20 per cent and a biomass productivity of around 70 g $m^{-2}$ $d^{-1}$ of Chlorella and others like *Phaeodactylum tricornutum* and *Tetraselmis suecica*.
4. AlgaeLink (The Netherlands) has developed the first made-to-order industrial algae production facility in the world. The company started selling its AlgaeLink tubular photobioreactor system for producing 1 to 100 dry-weight tons of biomass per day. AlgaeLink is a closed system consisting of clear tubes 36 metres (118 feet) long and 64 centimetres (25 inches) in diameter. The economics of their system are given in Table 24.8.

**Table 24.8** Economics of algae link photobioreactor.

| Capacity (tons/day) | Length (m) | $CO_2$ (kg/day) | Area (acres) | Electricity (kW) | Cost (Euros) |
|---|---|---|---|---|---|
| Demo | 36 | 10 | 0.01 | 12 | 69,000 |
| 1 | 1068 | 2881 | 0.4 | 55 | 5,80,000 |
| 10 | 10,692 | 28,805 | 4.3 | 545 | 2.5 million |
| 50 | 53,466 | 1,44,027 | 22 | 2727 | 6 million |
| 100 | 1,06,932 | 2,88,053 | 44 | 5455 | 10 million |

*Note:* The company has 25 tons/day and 75 tons/day capacity plants.

5. Solazyme has a unique process that grows algae in the dark using standard industrial bio-production equipment, where the algae are fed a variety of nonfood and waste biomass materials including cellulosic biomass and low-grade glycerol. This allows the company to produce oil with a very low carbon footprint efficiently in a controlled environment. Recently they produced the world's first algal-based jet fuel which met all eleven of the tested key criteria for (ASTM) D1655 (Jet A-1). Additionally, the process developed is the very first bridge from nonfood carbohydrates and certain industrial waste streams to edible oils and oleochemicals.
6. Infinifuel Biodiesel LLC, using Nevada's renewable geothermal resources to heat and power the plants, has come up with an innovative idea to build a geothermal powered and heated biodiesel plant based on algae oil.
7. Aquaflow Bionomic Corporation (ABC), New Zealand has produced the first sample of biodiesel fuel made from algae found in sewage ponds. A paper from Michael Briggs, at the UNH Biodiesel Group, offers estimates for realistic replacement of all vehicular fuel with biodiesel by utilising algae that have a natural oil content greater than 50 per cent, which Briggs suggests can be grown on algae ponds at waste-water treatment plants.
8. California-based Origin Oil Inc. has successfully automated its algae cultivation and oil extraction system, allowing it to grow algae to extract the oil for biodiesel production.
9. The BioFence photobioreactor is an efficient and reliable method for producing high density monocultures of marine and freshwater algae. The BioFence has been in production for these markets for the past five years, where it has yielded up to 140 grams per day in a 200 litre system. This output is much higher than a raceway pond or bag-type reactor. All parameters of the photosynthetic process—temperature, light, nutrients and carbon dioxide are controlled to increase production rates. This in turn makes the algae farm profitable and gives it the ability to provide enough extra revenue to cover the expenses of an indoor environmentally controlled facility.
10. A hybrid system is another option for the mass production of algal biomass. This system would employ both a raceway pond and photobioreactors. The photobioreactor would provide a continuous supply of high-density monoculture algae for further propagation and lipid oil production. The major advantage to a hybrid system is that it reduces a large amount of the capital expense for installation.

11. Culturing solutions has developed a low kilowatt consumption process to extract algae from the oil. It utilises the remaining water in the algae slurry as a solvent along with a reactor to rupture the cell walls releasing the lipids. The downstream process further separates the remaining biomass, algae oil and water. And the oil can be dehydrated for transesterification.
12. University of Nevada, Reno has successfully demonstrated the first real-world project in Nevada for turning algae into biofuel. University researchers have harvested their first outdoor cold-weather crop of algae as a part of their collaborative algae-to-biofuels project with their industry partners Enegis, LLC and Bebout and Associates. The project, using one of two 5000 gallon ponds at the University's greenhouse complex on Valley Road in Reno, produced several hundred gallons of concentrated algal slurry. A conservative estimate for this harvest is 30 per cent lipids and 5 per cent starches on a dry weight basis, less on a fresh weight basis.
13. Aircraft manufacturer Boeing has led a multidisciplinary initiative to promote the development of algal biofuels, the algal biomass organisation (ABO). Joined by several of its airline customers, the organisation is looking to take up the work left by DOE's investigation in the field through its aquatic species program (ASP), aiming at sourcing renewable fuels for aerospace industry. It will be a biggest online authentic, legitimate scientific repository of developments in algae-based fuels screened through various interdisciplinary intellectuals in the field including people from industry, government and investment groups.

Tremendous development efforts were seen in the last five years through various collaborations, moving from small research labs to pilot projects or to small scale demonstration projects, and now to first-stage commercial projects. Although production of algae is still not a commercially viable fuel, there are several indicators that suggest the algae-based fuels will become price-competitive with petroleum fuels in the next few years. At the beginning of 2009 the cost to produce a gallon of algae oil was estimated between US $8 and $20. However, the initial findings of the Algae 2020 study present a best-case scenario where some projects may advance to early-adopter stage commercial viability by the end of 2010; and a baseline scenario closer to 2012 with wider market adoption due to technology acceleration, increased competition, and eventually greater market penetration based on price-competitive fuels. Biodiesel producers capable to evolve and adapt to transitions in technology, markets, feedstocks and government policies are most likely to succeed over the long-term.

## 24.16 Technical and research challenges to overcome

Algae are the fastest-growers of the plant kingdom. But if it were easy to extract the fuel, most of the world's biodiesel would have been already made from microalgae, grown on non-agricultural land, close to coalfired power plants. The extensive ongoing research at various levels is on how to cultivate algae better, how to select the right algae species, such as in outdoor ponds or more expensive photobioreactors, which are large, expensive indoor facilities where researchers or producers can closely control variables such as nutrients, pH, temperature and light, to examine the process of harvesting techniques and how to 'scale-up' laboratory successes into industrial-level production. Some of the highlighted areas along with the associated problems across the world are:

1. *Cost of reactor:* Photobioreactor which are used now-a-days are highly priced (on comparing the process with growing rapeseed or corn in greenhouses). Open pond system is an alternative low cost idea, but then the algae cultures become unstable with high drops in biomass productivity, yielding even less usable biomass than an average sugarcane or palm oil plantation. Open algal ponds are subjected to evaporation and rainfall, which causes imbalances in salinity and pH. Since algae need water as a medium, both water requirements and the costs to process the wet algae are high.
2. Genetically modified algae might be more stable, but then the environmental risks remains that are extremely high (pollution and destruction of the biodiversity in water bodies and rivers).
3. *Operational parameters:* Temperature must be constant because too much direct sunlight can kill algae. It needs only about l/10th the amount of light they receive from direct sunlight. Direct sunlight is often too strong for algae. Since overcrowding inhibits their growth, they must be displaced after growth. In most of the algal-cultivation systems, light penetrates the top 3–4 inches of the water. This is because as the algae grow and multiply, they become so dense that they block light from reaching deeper into the pond or tank. The waste oxygen released by algae must be continually removed from the water to avoid inhibition in photosynthesis.
4. *Gap between laboratory and field:* The laboratory-level screening protocols and lipid productivities were unable to demonstrate the same in outdoor ponds.
5. *The difficulties in efficient biodiesel production from algae:* The difficulties in efficient biodiesel production from algae lie not only

in the extraction of the oil, but also in finding an algal strain with a high lipid content and the growth rate that should not be too difficult to harvest, and a cost-effective cultivation system (i.e. type of photobioreactor) that is best suited to that strain.

6. *Obstacles by governing bodies:* To get an industrial plant built, developers need to find a site with easy access to infrastructure for water, power and transportation yet not too close to residential or commercial areas that may object to noise, traffic, odour or any number of other inconveniences.
7. *Low value product:* Biodiesel from algae is actually a low-value product as there are a number of companies successfully growing algae for the lucrative nutraceutical market where products are sold for hundreds if not thousands of dollars per gallon. Nevertheless, there are a number of uses for algae beyond just biodiesel, i.e. animal feed, omega three oils, and aviation fuel.
8. *Technology yet to be proven on commercial scale:* Producing algae is the first step in the process of creating an economically viable feedstock. Algae have to be harvested and concentrated into a thick paste, before extracting the oil. A number of pilot plants out there can be scaled up to a commercial size for growing algae, but downstream processes (harvesting and dewatering) still need to be proven on a commercial scale.
9. *Promise for the near future:* Even though the potential for algae has been studied for decades, as an industry it is still in its infancy. Most firms are still at the preventure capital stage. However, a few firms have received significant amounts of money from farsighted investors. The national algae association (NAA) and algae biomass organisation (ABO) are holding regular meetings to bring developers, academics, investors and potential customers together to accelerate the development of the industry. Algae-energy research is bubbling with new ideas and talent and is beginning to get backing from venture capital. Earlier the money in this area went only to academics, now it is reaching entrepreneurs who are applying technologies that did not exist 10 or 15 years ago.

# 25
# Nanotech biofuels and fuel additives

## 25.1 Introduction

This chapter focuses on reviewing the application of nanotechnology to biofuels production and to the utilisation of fuel additives, some of which are derived from renewable materials. To introduce the topic, the broader context of petroleum fuels and biofuels is presented. A smart future of oil refining would be to increasingly utilise margins to finance a transition away from oil towards future alternative providers of mobility, in particular biofuels. Future scenarios of liquid biofuels involve the market penetration of second and further generations of technologies and the continuous improvement of first generation processes. On the other hand, nanotechnologies are among the candidate technologies for the biofuels of the future. The nanotechnology field is vast and its applications unbound.

This is followed by a brief review of nanotechnology developments, especially as they apply to liquid particles, beyond the more common solid particle applications. Algae growth, harvesting and conversion are presented and discussed, given the immense potential of their contribution towards an energy future where biofuels play a significant role.

Most of the current effort in second generation conversion to liquid biofuels is based on biomass cellulosics to ethanol and biodiesel. Nano processes are being pursued and will be reviewed in the chapter. Likewise, the presently used processes to convert oils and animal fat into biodiesel are based on trans-esterification with methanol or ethanol, which inevitably generates glycerol, which must find a market or get disposed properly. Nano processes may be useful in addressing this issue.

Speculative considerations are made about the role of liquid nanoparticles of fuel additives in enhancing the performance of additised biofuel/fuel blends, in connection with surface and combustion effects. Public concerns over the impacts of nanotechnologies on security, health and the environment are also mentioned and discussed. But, a cautionary optimistic view is presented on the huge benefits of a careful penetration of nanotechnologies in the realm of biofuels and fuel additives, and in many more applications, especially those dealing with human health.

## 25.2 Future of oil refining and the oil transition to alternatives

Crucial challenges to the oil industry are evolving, as the demand for energy services (mobility, lighting, rotary movement, heating and cooling) increases, which with the current technology setup, is translated into expanding demand for liquid fossil fuels. Oil producers and refiners face difficulties finding sufficient good quality crude oil in adequate amounts and reasonable costs to meet growing demand over the long run, while users and the public at large are pushing for environmental improvements, such as better air quality in the immediate future. Moreover, concerns about the impacts of climate change caused by increased greenhouse gases emissions from the production and use of liquid hydrocarbons may eventually force a transition to climate friendly energy services providing systems. This offers biofuels a market penetration opportunity in the transition towards a yet undefined new energy future.

Under this background, the oil refining industry in the USA and the European Union has been stagnant. It has been immobilised by environmental obstacles posed by an articulated public, augmented by a ‘not in my backyard’ attitude that makes it difficult to build new refineries. In addition, declining margins for refined products may have led major players to focus more on the upstream.

On the other hand, refining is expanding in other parts of the world, such as India, China, Brazil and the Middle East, as these countries develop and the oil producers attempt to add more value to their resources. An evidence of the shift of refining towards developing economies is the fact that the largest refinery in the world is in India and belongs to Reliance. But, all over the world, the increase in the long-term marginal cost of oil combined with environmental pressures and stricter government regulations and mandates are likely to lead to the decline of the centrality of oil in the global energy mix in favour of natural gas. This shift in dominance happened to wood and coal over the past two centuries and is now happening to oil. Oil companies are increasingly calling themselves energy companies. Some of them will leverage their current oil production margins to make a smooth transition to alternatives over time. A profitable transition to alternatives in the oil economy would require a gradual transfer of oil profits into green investments and the stretching of current oil supplies.

## 25.3 Liquid biofuels issues

The enormous global daily consumption of liquid fuels is of the order of 80 million barrels/day (equivalent of 12.7 million $m^3$/day). The sugar cane area required to produce the same volume of ethanol is about 700 million hectares, assuming a yield of 6.5 $m^3$/ha/year of ethanol. This area is equivalent to 100 times the sugar cane cultivated area in Brazil, the second largest bioethanol producer in the world. Biofuels definitely face an issue of scale. In 2010, fuel ethanol and biodiesel combined displaced a mere 3 per cent of oil in the world.

Algae require the least area to meet the large scale demand of liquid fuels in the USA, whereas the area required by soyabeans is larger than the USA's 48 continental states. The area required by corn is substantial. This suggests that the current biofuels production base of the USA would not be able to meet demand, and imports would be required to meet the colossal American energy appetite.

The scale challenge posed to biofuels relates to the labour, management, land, water and sunshine required to produce the biomass and the processing that originates them. These are scarce resources that are also needed to grow food, feed and fibre to ultimately meet various human demands. These are resources that have an opportunity cost from competing markets. To develop biofuels in the scale of commercial liquid fuels require massive financing, a resource that may have alternative uses as well. The mobilisation of private capital under a perception of market and other uncertainties is another issue that biofuels have to resolve in order to thrive.

The production of biofuels is accompanied by local environmental issues that need addressing. For instance, in the case of sugar cane ethanol, stillage the liquid residue of distillation, has a high chemical and biological oxygen demand and requires appropriate processing before final disposal. From a global climate change perspective, designed and managed properly, a biofuels production system would add minimally to greenhouse gas emissions. But, in practice, many biofuel production systems in the world are contributing net GHG emissions.

A bone of contention in the development of the biofuels industry is the present competition for feedstocks between the food and fuel industries. In the case of biodiesel, all commercial vegetable oils that are used in preparing food are also convertible to biodiesel. A similar situation exists with respect to fuel ethanol, especially for the starch-based feedstocks (corn and wheat). However, the hike in food prices that happened globally in 2007/2008 and is happening in 2010/20l1 derive mostly from other causes such as droughts and other climate related phenomena, higher oil prices and market speculation.

Since the cost of biofuels is dominated by feedstocks cost, access to feedstocks in the required amounts, timing and at adequate prices is key to the success of the biofuels economy. The combination of the food versus fuel conundrum with the need to have reliable and economic access to feedstocks is shifting the industry towards non-food feedstocks and to the market penetration of second generation technologies to convert cellulosic biomass into liquid biofuels.

Concern in important consuming markets about the sustainability of biofuels producing systems is putting pressure on suppliers to abide by sustainability protocols subject to certification. The sustainability of biofuels is actually linked to freer international trade, which would tend to phase out unsustainably produced biofuels in favour of regions of the world that can meet sustainable production requirements. A valuable discussion on this matter was hosted by the Rockefeller Foundation in 2008 at its Bellagio Centre and produced a sustainable biofuels consensus. The objective was to understand the many drivers for sustainable trade, consumption and production of biofuels, and the comparative advantage of supplying regions combined with demand and technology from consuming regions.

However, much remains to be done to achieve free international trade of biofuels. The World Trade Organisation Doha rounds have reached an impasse. Currently, biodiesel is considered an industrial product, whereas fuel ethanol is categorised as an agricultural product, which allows more protectionism. What is needed is a unified treatment of biofuels, where they are classified under environmental goods and services. But, irrespective of these drawbacks, a sign pointing to a larger role for biofuels in the future are the new biofuels technology initiatives by large oil companies, such as BP, Chevron, Exxon and Shell. The development of the international trade in biofuels is likely to distribute more evenly the production and consumption of biofuels in the world. For the time being, biofuels production is overwhelmingly concentrated in the USA, Brazil and the European Union.

## 25.4 Vastness of nanotechnology

Nanotechnology can be simply defined as the discipline of building machines/devices on the scale of molecules, a few Nanometres (10–9 m) wide, way smaller than a cell. Table 25.1 shows some practical applications of nanotechnologies and confirms the vastness of their domain.

**Table 25.1** Some applications of nanotechnology.

| | |
|---|---|
| Nanocrystalline drugs | Oxide nanoparticles |
| Nanofilm coatings | Carbon nanotubes |
| Cosmetics | Silicon nanomaterials |
| Nanocatalysts | Metal nanoparticles |
| Ceramics | Polymer nanocomposites |
| Rubbers | Inorganic nanocrystals |

In the practically important area of polymers, nanotechnologies originate nanostructured polymers, where applications can be found in support structures, manufacturing processes, diagnostics and therapy, pharmaceuticals, medical and dental prosthesis, and thin films for surface treatment. The main chemicals involved in nanostructured polymers are poly-oxides, poly-acrylates, poly-vinylics, poly-saccharides and poly-ethylenes. The main materials incorporated into polymer nano-matrices are silicon, chromium and carbon.

## 25.5 Turning algae into biofuels

Biofuels derived from algae offer a great potential in view of the possible high yields and smaller area requirements. In addition, algae can play a role in carbon mitigation, as one way of growing algae is to feed them carbon dioxide ($CO_2$), besides water and sunlight. Algae can be fed other substrates as well, because to grow, cost-effectively, on carbon dioxide there would be a need of concentrated sources of the gas, such as found in combustion off-gases from fossil fuelled power plants.

Oil can form up to 50 per cent of the algae mass, in contrast with the best oil-bearing plants—oil palm trees—where less than 20 per cent of the biomass is made out of foil. Algae carbohydrates can also be made into ethanol or gasified into biogas or methane or hydrogen.

But, algae development into biofuels must overcome a number of challenges before algae can become significant sources of commercial biofuels. Since algae also need water to grow, expansion of algae production may create a dilemma of water versus fuel, similar to food versus fuel dilemma discussed previously. Another challenge is the low natural carbon dioxide concentration in the atmosphere, hence the consideration of additional sources of carbon for algal growth in a commercial biofuels system. One response to these challenges may include the use of nanotechnology to turn algae into biofuels.

As way of examples, in 2009, the company QuantumSphere received a grant from the California Energy Commission to develop a nanocatalysed algae biogasification. Also in California, the Salton Sea receives large amounts of agricultural runoff, which sometimes create large algae blooms. These algae and similar biomass have been turned experimentally into methane, hydrogen and other gases.

One nanotechnology relevant to algae development is the use of nanoparticles as no-harm harvesters of biofuel oils from algae, as illustrated in Fig. 25.1. The nanoparticles are shown on the left hand side of the photograph before the oil pregnant algae are added.

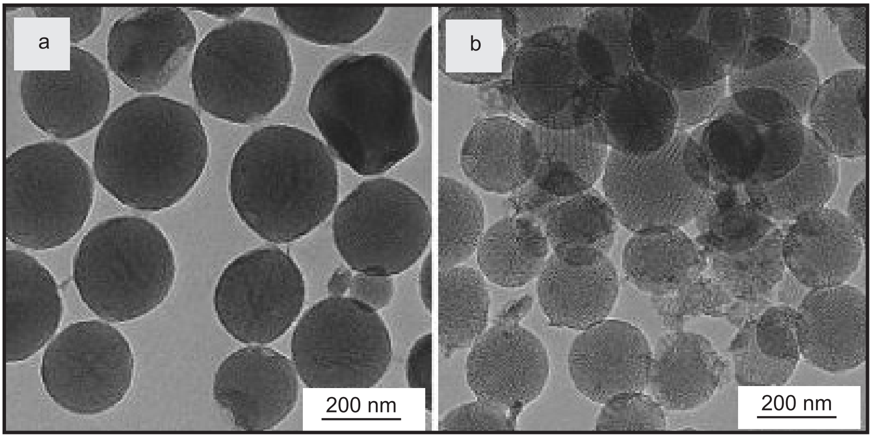


**Figure 25.1** Nanoparticles harvesting oil from algae without harming the organism

The right hand side shows the contacting between the algae and the nanoparticles, which results in extracting the oil without harming the algae. Maintaining the algae alive can dramatically reduce production costs and the generation cycle.

One possible downside of the nano-harvesters is the risk that they may be released into the environment, although the spherical nanoparticles are made of calcium compounds and sand. The pores of the spheres are lined with chemicals, which extract algal oil without breaking the cell membrane. Nevertheless, prior to commercial market penetration of nano-harvesting, there would be a need to carry out due diligence to ensure the safety of these processes.

## 25.6 Nanotechnology applied to landfill facilities

The organic matter in landfills tend to undergo anaerobic fermentation yielding methane and $CO_2$, which if naturally vented into the atmosphere would add to the greenhouse emissions that warm the climate. And the climate change impact of methane is 25 times larger than that of carbon dioxide for a time horizon of 100 years. Thus, there is a need to sequester the carbon present in landfill methane. Nanocatalysts can crack methane into elemental carbon and hydrogen. The carbon can be produced in high-purity nano-graphite for use in aerospace, automobile, batteries, etc. This approach to handling methane can considerably improve the economics of landfills as well as of anaerobic digester plants that generate electricity from biogas fuelled electricity.

## 25.7 Nanotechnology to convert biomass into biofuels

Delinking biofuels production from food crops is a necessary condition to expand the scale of the market penetration of biofuels globally. Among the challenges this strategy faces is the inherent resistance of cellulosic feedstocks to conversion to simpler sugars that can be fermented into ethanol. Here, the promise lies in nanoparticles used as immobilising beds for expensive enzymes that can be used over and over again to breakdown the long chain cellulose polymers into simpler fermentable sugars.

The Louisiana Tech University is one among many organisations worldwide engaged in this endeavour, through the work of Dr. James Palmer, in collaborating with fellow professors Dr. Yuri Lvov, Dr. Dale Snow, and Dr. Hisham Hegab. The focus is on nonedible cellulosic biomass, such as wood, grass, stalks, etc. to be converted into ethanol. This approach to produce ethanol can reduce GHG emissions by some 86 per cent over fossils fuels.

The broader field of nanotechnology research into converting biomass into biofuels is growing fast. For example, in 2007 the oil company BP has granted a research fund of $500 million to the University of California, at Berkeley, and the University of Illinois, to explore the conversion of corn, plant material, algae and switch grass into fuel.

In the past, Berkeley had used nanotechnology in research for cost-effective solar panels. But, the new Energy Biosciences Institute (EBI) created at Berkeley will focus on fuel production with minimum environmental impacts and carbon emissions. A three pronged approach is being employed that begins with technologies for better crop production, improved feedstocks processing and development of new biofuels. The application of this approach aims at developing better feedstocks, breaking down plant material into sugars and their conversion to ethanol.

Success along this pathway is expected to lead EBI to investigate the use of nanotechnology to develop other alternative fuels, such as butanol and renewable hydrocarbon fuels. Another relevant application of nanotechnology is the use of nano-catalysts for the trans-esterification of fatty esters from vegetable oils or animal fats into biodiesel and glycerol. The nano-catalyst spheres replace the commonly used sodium methoxide. The spheres are loaded with acidic catalysts to react with the free fatty acids and basic catalysts to react with the oils. This approach eliminates several production steps of the conventional process, including acid neutralisation, water washes and separations. All those steps dissolve the sodium methoxide catalyst so it cannot be used again. In contrast, the catalytic nanospheres can be recovered and recycled.

The overall result is a cheaper, simpler and leaner process. In summary, the process claims to be economical, recyclable, to react at mild temperatures and pressures, with both low and high FFA (free fatty acid) feedstock, producing cleaner biodiesel and cleaner glycerol, greatly reducing water consumption and environmental contaminants, and can be used in existing facilities.

## 25.8 Nanotech liquid additives

All previous presentation and discussion referred to solid nanoparticles playing a catalytic role in the obtaining biofuels from algae, landfill methane and biomass. The following segments will examine the practical opportunities that exist for liquid nanoparticles or droplets. Consider multifunctional surface active liquid additives, whose lubricity enhancement is achieved via the formation of a monolayer over the surfaces in contact with additised fuel. The treat rate for lubricity is determined by the adsorption saturation concentration. Speculate that the improved detergency and water co-solvency is obtained by the formation of nano-emulsions. Also, postulate that the more complete combustion and consequent fuel efficiency increase is the result of the behaviour of nano droplets. These nano droplets result from the surfactant action of the additive in the fuel formulation and the presence of some water in all commercial fuel systems, usually due to evening condensation. Research by Wulff and colleagues has shown that nano-emulsions, which the authors call micro-emulsions, with fuel (biofuel included most likely), water and surfactant are:

1. Thermodynamically stable
2. Microscopically isotropic
3. Nanostructured (thus, nano-emulsions)

Their research concluded that:

1. The use of these nanostructures with fuel, water and surfactant is able to break the usual trade off between reduction of soot and NOx emissions, by achieving them simultaneously.
2. For the same fuel consumption, higher efficiency is obtained.

Strey and collaborators filed patent applications for what they call micro-emulsions used as fuel. The interpretation offered for the behaviour of stable diesel (and most likely biodiesel)-water-surfactant nanoemulsions is as follows:

1. The surfactant components—oleic acid and nitrogen containing compounds (amines)—dissolve readily in diesel (and possibly in biodiesel) fuel and bind water to it without stirring.
2. The water droplets are as small as a nanometre across, helping stabilise the emulsion.

3. The result is a ‘liquid sponge’, can be stored indefinitely, like ordinary diesel fuel, without risk of phase separation.
4. This fuel formulation, when burned, results in the near-complete elimination of soot, and a reduction of up to 80 per cent in nitrogen-oxide emissions.
5. The surfactant in the formulation also burns without creating emissions beyond water, carbon dioxide and nitrogen.

## 25.9 Public concerns over nanotechnology: security, health and the environment

As with all new technologies, there may be cause to concern about impacts, such as on security, health and the environment. Nanotechnologies have been the subject of many assessments seeking to anticipate possible consequences of their deployment, to humans and to the environment.

The fact is that ‘most people have no clear associations when it comes to nanotech. They expect economic benefits but no revolutionary technological breakthroughs. Risks are often not explicitly mentioned but there is a concern for unforeseen side effects. There is a latent concern about industry, science and politics building a coalition against public interest. And one negative incident could have a major negative impact on public attitudes.’

## 25.10 Conclusion

Increasing demand for energy services in the decades ahead will require an expanding supply of liquid fuels, despite efforts at improving energy efficiency and diversification of energy systems, including growing use of electricity in transportation. Biofuels have a key role to play in this scenario. However, the future supply of biofuels must be of such a scale that non-food feedstocks and new technologies are intensively employed. Nanotechnologies are primary candidates to play a prominent role in this energy future. They will help bring to markets liquid biofuels, including renewable hydrocarbons, from algae, carbohydrates, fatty esters and biogas. Nanotechnologies will also play a role in augmenting the efficiency of using current and future liquid fuels, especially biofuels, by providing improved combustion of nanodroplets. While there are risks in each and every new technology, the world today is much better equipped to assess risks and act accordingly, that it seems possible to advance nanotechnologies applied to biofuels, without jeopardising security, public health or the environment. But, the reach of nanotechnologies is vast and goes much beyond biofuels and offer hopes in so many areas, including importantly, human health.

# 26
# Issues relating to biofuels

## 26.1 Introduction

There are various current issues with biofuel production and use. These include: the effect of moderating oil prices, the 'food vs. fuel' debate, carbon emissions levels, sustainable biofuel production, deforestation and soil erosion, impact on water resources, human rights issues, poverty reduction potential, biofuel prices, energy balance and efficiency, and centralised versus decentralised production models.

## 26.2 Issues related to biofuels

### 26.2.1 Oil price moderation

The International Energy Agency's World Energy Outlook 2006 concludes that rising oil demand, if left unchecked, would accentuate the consuming countries' vulnerability to a severe supply disruption and resulting price shock. The report suggested that biofuels may one day offer a viable alternative, but also that 'the implications of the use of biofuels for global security as well as for economic, environmental, and public health need to be further evaluated'. According to Francisco Blanch, a commodity strategist for Merrill Lynch, crude oil would be trading 15 per cent higher and gasoline would be as much as 25 per cent more expensive, if it were not for biofuels. Gordon Quaiattini, president of the Canadian Renewable Fuels Association, argued that a healthy supply of alternative energy sources will help to combat gasoline price spikes.

### 26.2.2 Food versus fuel debate

Food vs. fuel is the dilemma regarding the risk of diverting farmland or crops for biofuels production in detriment of the food supply on a global scale. The 'food versus fuel' or 'food or fuel' debate is internationally controversial, with good-and-valid arguments on all sides of this ongoing debate. There is disagreement about how significant this is, what is causing it, what the impact is, and what can or should be done about it.

## 26.2.3 Carbon emissions

Biofuels and other forms of renewable energy aim to be carbon neutral or even carbon negative. Carbon neutral means that the carbon released during the use of the fuel, e.g. through burning to power transport or generate electricity, is reabsorbed and balanced by the carbon absorbed by new plant growth. These plants are then harvested to make the next batch of fuel. Carbon neutral fuels lead to no net increases in human contributions to atmospheric carbon dioxide levels, reducing the human contributions to global warming. A carbon negative aim is achieved when a portion of the biomass is used for carbon sequestration. Calculating exactly how much greenhouse gas (GHG) is produced in burning biofuels is a complex and inexact process, which depends very much on the method by which the fuel is produced and other assumptions made in the calculation.

The carbon emissions (carbon footprint) produced by biofuels are calculated using a technique called life cycle analysis (LCA). This uses a 'cradle to grave' or 'well to wheels' approach to calculate the total amount of carbon dioxide and other greenhouse gases emitted during biofuel production, from putting seed in the ground to using the fuel in cars and trucks. Many different LCAs have been done for different biofuels, with widely differing results. Several well-to-wheel analysis for biofuels has shown that first generation biofuels can reduce carbon emissions, with savings depending on the feedstock used, and second generation biofuels can produce even higher savings when compared to using fossil fuels. However, those studies did not take into account emissions from nitrogen fixation or additional carbon emissions due to indirect land use changes.

In October 2007, a study was published by scientists from Britain, US, Germany and Austria, including Professor Paul Crutzen, who won a Nobel Prize for his work on ozone. They reported that the burning of biofuels derived from rapeseed and corn (maize) can contribute as much or more to global warming by nitrous oxide emissions than cooling by fossil fuel savings. Nitrous oxide is both 296 times more powerful a greenhouse gas than carbon dioxide and a destroyer of atmospheric ozone. But they also reported that crops with lower requirements for nitrogen fertilisers, such as grasses and woody coppicing 'may also have moderately positive effects on climate, viewed solely from the perspective of $N_2O$ emissions'.

In February 2008, scientists investigated the GHG emissions effects of the large amount of natural land that is being converted to cropland globally to support biofuels development. The first of these studies, conducted at the University of Minnesota, examined the carbon debt produced by direct land use changes when pristine lands are clear for new crops destined for biofuel production, and found that:

Converting rainforests, peat lands, savannas or grasslands to produce food-based biofuels in Brazil, Southeast Asia, and the United States creates a 'biofuel carbon debt' by releasing 17 to 420 times more $CO_2$ than the annual greenhouse gas (GHG) reductions these biofuels provide by displacing fossil fuels.

This study not only takes into account removal of the original vegetation (as timber or by burning) but also the biomass present in the soil, for example roots, which is released on continued ploughing. It also pointed out that:

Biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials incur little or no carbon debt and can offer immediate and sustained GHG advantages.

The second study, conducted at Princeton University, used a worldwide agricultural model to estimate the indirect land use change impacts of biofuels (ILUC) as the US is expanding its croplands, which has the unintended of effect of releasing more $CO_2$ when farmers elsewhere in the world clear rainforests and other pristine lands to grow food crops to compensate for farmers in the US using their land to grow grain to produce ethanol, translating in a net increase in $CO_2$ emissions. The study concluded that:

Corn-based ethanol, instead of producing a 20 per cent savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years.

Both of the Science studies highlight the need for sustainable biofuels, using feedstocks that minimise competition for prime croplands. These include farm, forest and municipal waste streams; energy crops grown on marginal lands, and algae. These second generation biofuels feedstocks 'are expected to dramatically reduce GHGs compared to first generation biofuels such as corn ethanol'. In short, biofuels done unsustainably could make the climate problem worse, while biofuels done sustainably could play a leading role in solving the carbon challenge.

However, the estimation of carbon emissions due to ILUC effects has become one of the most contentious issues relating to biofuels, and it has been debated in the popular media, scientific journals, op-eds and public letters from members of the scientific community on both sides of the issue, and criticised by the ethanol industry, both American and Brazilian. This controversy has been intensified because the California Air Resources Board (CARB) adopted rules in April 2009 that included ILUC impacts to define the California Low-Carbon Fuel Standard that will enter into force in 2011. In May 2009 the US Environmental Protection Agency (EPA) released a notice of proposed rulemaking for implementation of the 2007 modification of the Renewable Fuel Standard (RFS), which also take into account the carbon emissions resulting from indirect land-use changes, causing additional controversy among ethanol producers and some politicians.

### 26.2.4 Sustainable biofuel production

Responsible policies and economic instruments would help to ensure that biofuel commercialisation, including the development of new cellulosic technologies, is sustainable. Sustainable biofuel production practices would not hamper food and fibre production, nor cause water or environmental problems, and would actually enhance soil fertility. Responsible commercialisation of biofuels represents an opportunity to enhance sustainable economic prospects in Africa, Latin America and impoverished Asia.

### 26.2.5 Soil erosion, deforestation and biodiversity

Large-scale deforestation of mature trees (which help remove $CO_2$ through photosynthesis—much better than does sugar cane or most other biofuel feedstock crops do) contributes to unsustainable global warming atmospheric greenhouse gas levels, loss of habitat, and a reduction of valuable biodiversity (both on land as in oceans). Demand for biofuel has led to clearing land for 'Palm oil plantations'. In Sumatra and Borneo, over 4 million hectares of forest have been converted to palm farms and tens of millions more hectares are scheduled for clearance in Malaysia and Indonesia.

A portion of the biomass should be retained onsite to support the soil resource. Normally this will be in the form of raw biomass, but processed biomass is also an option. If the exported biomass is used to produce syngas, the process can be used to coproduce biochar, a low-temperature charcoal used as a soil amendment to increase soil organic matter to a degree not practical with less recalcitrant forms of organic carbon. For coproduction of biochar to be widely adopted, the soil amendment and carbon sequestration value of coproduced charcoal must exceed its net value as a source of energy.

### 26.2.6 Impact on water resources

Increased use of biofuels puts increasing pressure on water resources in at least two ways: water use for the irrigation of crops used as feedstocks for biodiesel production; and water use in the production of biofuels in refineries, mostly for boiling and cooling.

In many parts of the world supplemental or full irrigation is needed to grow feedstocks. For example, if in the production of corn (maize) half the water needs of crops are met through irrigation and the other half through rainfall, about 860 litres of water are needed to produce one litre of ethanol. However, in the United States only 5–15 per cent of the water required for corn comes from irrigation while the other 85–95 per cent comes from natural rainfall.

In the United States, the number of ethanol factories has almost tripled from 50 in 2000 to about 140 in 2008. A further 60 or so are under construction, and many more are planned. Projects are being challenged by residents at courts in Missouri (where water is drawn from the Ozark Aquifer), Iowa, Nebraska, Kansas (all of which draw water from the non-renewable Ogallala Aquifer), central Illinois (where water is drawn from the Mahomet Aquifer) and Minnesota.

For example, the four ethanol crops: corn, sugarcane, sweet sorghum and pine yield net energy. However, increasing production in order to meet the US Energy Independence and Security Act mandates for renewable fuels by 2022 would take a heavy toll in the states of Florida and Georgia. The sweet sorghum, which performed the best of the four, would increase the amount of freshwater withdrawals from the two states by almost 25 per cent.

### 26.2.7 Aldehydes

Formaldehyde, acetaldehyde and other aldehydes are produced when alcohols are oxidised. When only a 10 per cent mixture of ethanol is added to gasoline (as is common in American E10 gasohol and elsewhere), aldehyde emissions increase 40 per cent. Some study results are conflicting on this fact however, and lowering the sulphur content of biofuel mixes lowers the acetaldehyde levels. Burning biodiesel also emits aldehydes and other potentially hazardous aromatic compounds which are not regulated in emissions laws.

Many aldehydes are toxic to living cells. Formaldehyde irreversibly cross-links protein amino acids, which produces the hard flesh of embalmed bodies. At high concentrations in an enclosed space, formaldehyde can be a significant respiratory irritant causing nose bleeds, respiratory distress, lung disease, and persistent headaches. Acetaldehyde, which is produced in the body by alcohol drinkers and found in the mouths of smokers and those with poor oral hygiene, is carcinogenic and mutagenic.

The European Union has banned products that contain formaldehyde, due to its documented carcinogenic characteristics. The US Environmental Protection Agency has labelled formaldehyde as a probable cause of cancer in humans.

Brazil burns significant amounts of ethanol biofuel. Gas chromatograph studies were performed of ambient air in São Paulo Brazil, and compared to Osaka Japan, which does not burn ethanol fuel. Atmospheric formaldehyde was 160 per cent higher in Brazil, and acetaldehyde was 260 per cent higher.

### 26.2.8 Environmental organisations' stance

A number of environmental NGOs campaign against the production of biofuels as a large scale alternative to fossil fuels. For example, friends of the earth state that 'the current rush to develop agrofuels (or biofuels) on a large scale is ill-conceived and will contribute to an already unsustainable trade whilst not solving the problems of climate change or energy security'. Some mainstream environmental groups support biofuels as a significant step toward slowing or stopping global climate change. However, supportive environmental groups generally hold the view that biofuel production can threaten the environment if it is not done sustainably. This finding has been backed by reports of the UN, the IPCC, and some other smaller environmental and social groups as the EEB and the Bank Sarasin, which generally remain negative about biofuels.

As a result, governmental and environmental organisations are turning against biofuels made in a nonsustainable way (hereby preferring certain oil sources as jatropha and lignocellulose over palm oil) and are asking for global support for this. Also, besides supporting these more sustainable biofuels, environmental organisations are redirecting to new technologies that do not use internal combustion engines such as hydrogen and compressed air.

The 'Roundtable on Sustainable Biofuels' is an international initiative which brings together farmers, companies, governments, non-governmental organisations, and scientists who are interested in the sustainability of biofuels production and distribution. During 2008, the Roundtable is developing a series of principles and criteria for sustainable biofuels production through meetings, teleconferences, and online discussions.

The increased manufacture of biofuels will require increasing land areas to be used for agriculture. Second and third generation biofuel processes can ease the pressure on land, because they can use waste biomass, and existing (untapped) sources of biomass such as crop residues and potentially even marine algae.

In some regions of the world, a combination of increasing demand for food, and increasing demand for biofuel, is causing deforestation and threats to biodiversity. The best reported example of this is the expansion of oil palm plantations in Malaysia and Indonesia, where rainforest is being destroyed to establish new oil palm plantations. It is an important fact that 90 per cent of the palm oil produced in Malaysia is used by the food industry; therefore biofuels cannot be held solely responsible for this deforestation. There is a pressing need for sustainable palm oil production for the food and fuel industries; palm oil is used in a wide variety of food products. The Roundtable on Sustainable biofuels is working to define criteria, standards and processes to promote sustainably produced biofuels. Palm oil is also used in the manufacture of detergents, and in electricity and heat generation both in Asia and around the world (the UK burns palm oil in coal-fired power stations to generate electricity).

Significant area is likely to be dedicated to sugar cane in future years as demand for ethanol increases worldwide. The expansion of sugar cane plantations will place pressure on environmentally-sensitive native ecosystems including rainforest in South America. In forest ecosystems, these effects themselves will undermine the climate benefits of alternative fuels, in addition to representing a major threat to global biodiversity.

Although biofuels are generally considered to improve net carbon output, biodiesel and other fuels do produce local air pollution, including nitrogen oxides, the principal cause of smog.

### 26.2.9 Potential for poverty reduction

Researchers at the overseas development institute have argued that biofuels could help to reduce poverty in the developing world, through increased employment, wider economic growth multipliers and energy price effects. However, this potential is described as ‘fragile’, and is reduced where feedstock production tends to be large scale or causes pressure on limited agricultural resources: capital investment, land, water, and the net cost of food for the poor.

With regards to the potential for poverty reduction or exacerbation, biofuels rely on many of the same policy, regulatory or investment shortcomings that impede agriculture as a route to poverty reduction. Since many of these shortcomings require policy improvements at a country level rather than a global one, they argue for a country-by-country analysis of the potential poverty impacts of biofuels. This would consider, among other things, land administration systems, market coordination and prioritising investment in biodiesel, as this ‘generates more labour, has lower transportation costs and uses simpler technology’. In 2008 the British anti-poverty charity War on Want released a report linking the demand for biofuels and other ‘green’ alternatives to petroleum to violent land seizures taking place in Colombia. The report outlines how the production of biofuels, specifically palm oil, has led to the forced displacement of thousands of Afro-Colombians from the south-west region of Colombia.

### 26.2.10 Energy efficiency and energy balance of biofuels

Production of biofuels from raw materials requires energy (for farming, transport and conversion to final product, and the production/application of fertilisers, pesticides, herbicides, and fungicides), and has environmental consequences.

The energy balance of a biofuel (sometimes called ‘net energy gain’) is determined by the amount of energy put into the manufacture of fuel compared to the amount of energy released when it is burned in a vehicle.

This varies by feedstock and according to the assumptions used. Biodiesel made from sunflowers may produce only 0.46 times the input rate of fuel energy. Biodiesel made from soyabeans may produce 3.2 times the input rate of fossil fuels. This compares to 0.805 for gasoline and 0.843 for diesel made from petroleum. Biofuels may require higher energy input per unit of Btu energy content produced than fossil fuels. Petroleum can be pumped out of the ground and processed more efficiently than biofuels can be grown and processed. However, this is not necessarily a reason to use oil instead of biofuels, nor does it have an impact on the environmental benefits provided by a given biofuel.

Studies have been done that calculate energy balances for biofuel production. Some of these show large differences depending on the biomass feedstock used and location.

To explain one specific example, a June 17, 2006 editorial in the Wall. St. Journal stated, ‘The most widely cited research on this subject comes from Cornell’s David Pimental and Berkeley’s Ted Patzek. They’ve found that it takes more than a gallon of fossil fuel to make one gallon of ethanol 29 per cent more. That’s because it takes enormous amounts of fossil-fuel energy to grow corn (using fertiliser and irrigation), to transport the crops and then to turn that corn into ethanol’.

Life-cycle assessments of biofuel production show that under certain circumstances, biofuels produce only limited savings in energy and greenhouse gas emissions. Fertiliser inputs and transportation of biomass across large distances can reduce the GHG savings achieved. The location of biofuel processing plants can be planned to minimise the need for transport, and agricultural regimes can be developed to limit the amount of fertiliser used for biomass production. A European study on the greenhouse gas emissions found that well-to-wheel (WTW) $CO_2$ emissions of biodiesel from seed crops such as rapeseed could be almost as high as fossil diesel. It showed a similar result for bioethanol from starch crops, which could have almost as many WTW $CO_2$ emissions as fossil petrol. This study showed that second-generation biofuels have far lower WTW $CO_2$ emissions.

Other independent LCA studies show that biofuels save around 50 per cent of the $CO_2$ emissions of the equivalent fossil fuels. This can be increased to 80–90 per cent GHG emissions savings if second generation processes or reduced fertiliser growing regimes are used. Further GHG savings can be achieved by using by-products to provide heat, such as using bagasse to power ethanol production from sugarcane.

Collocation of synergistic processing plants can enhance efficiency. One example is to use the exhaust heat from an industrial process for ethanol production, which can then recycle cooler processing water, instead of evaporating hot water that warms the atmosphere.

### 26.2.11 Biofuels and solar energy efficiency

Biofuels from plant materials convert energy that was originally captured from solar energy via photosynthesis. A comparison of conversion efficiency from solar to usable energy (taking into account the whole energy budgets) shows that photovoltaics are 100 times more efficient than corn ethanol and 10 times more efficient than the best biofuel.

### 26.2.12 Centralised versus decentralised production

There is debate around the best model for production. One side sees centralised vegetable oil fuel production offering:

1. Efficiency
2. Greater potential for fuel standardisation
3. Ease of administrating taxes
4. Possibility for rapid expansion

The other side of the argument points to:

1. Increased fuel security
2. Rural job creation
3. Less of a 'monopolistic' or 'oligopolistic' market due to the increased number of producers
4. Benefits to local economy as a greater part of any profits stay in the local economy
5. Decreased transportation and greenhouse gases of feedstock and end product
6. Consumers close to and able to observe the effects of production

The majority of established biofuel markets have followed the centralised model with a few small or micro producers holding a minor segment of the market. A noticeable exception to this has been the pure plant oil (PPO) market in Germany which grew exponentially until the beginning of 2008 when increasing feedstock prices and the introduction of fuel duty combined to stifle the market. Fuel was produced in hundreds of small oil mills distributed throughout Germany often run as part of farm businesses.

Initially fuel quality could be variable but as the market matured new technologies were developed that made significant improvements. As the technologies surrounding this fuel improved, usage and production rapidly increased with rapeseed oil PPO forming a significant segment of transportation biofuels consumed in 2007.

## 26.3 Biofuels: An important part of a low-carbon diet

To reduce transportation-related emissions—responsible for nearly 40 per cent of the United States' total global warming pollution—we need more efficient vehicles, fewer miles driven, and lower-carbon fuels (i.e. fuels that generate significantly less heat-trapping gases per unit of energy delivered than today's petroleum-based gasoline and diesel). Hydrogen, electricity, and biofuels (fuels produced from plants) all have the potential—if produced in a sustainable manner—to not only reduce transportation related emissions but also promote economic and energy security by curbing our country's growing oil dependence.

Biofuels can quickly become a staple of a low-carbon fuel diet because they integrate well with our existing fuel distribution infrastructure and offer potentially abundant domestic supplies with significant opportunities for growth. But not all biofuels are the same. There is a wide range in the estimated heat-trapping emissions and other environmental impacts from each biofuel over its life-cycle (i.e. from farm to finished fuel to use in the vehicle), depending on the feedstock, production process, and model inputs and assumptions. There are also concerns about emissions and impacts from land conversion and land use associated with biofuel production.

New rules are being developed that will require fuel providers to account for and reduce the heat-trapping emissions associated with the production and use of transportation fuels. For example, both the US Congress and Environmental Protection Agency (EPA) are considering strategies to promote low-carbon and renewable transportation fuels (including biofuels). California, the nation's largest market for transportation fuel, is developing a 'low carbon fuel standard' that will require fuel providers to demonstrate reductions in global warming pollution per unit of energy delivered, regardless of fuel source. More state, regional, and federal rules will undoubtedly follow.

The purposes of this report are two-fold:

1. To ensure that we 'count carbs' accurately, by explaining why we need a comprehensive accounting system for carbon emissions—one that measures global warming emissions over a transportation fuel's entire life-cycle. An effective accounting system will not only need to be robust enough to encompass the fuel life-cycle, but also address uncertainties and allow for changes overtime as better assessment tools and methods become available.
2. To 'make carbs count' by describing performance-based policies that will reward low-carbon transportation fuels for their performance and help them compete against highly polluting fuels such as liquid coal (gasoline or diesel made from coal). For example, low-carbon

fuel standards require a reduction in the average amount of global warming pollution per gallon of fuel.

A market for low-carbon fuels can produce a rare convergence of business, agricultural, and environmental interests that, if pursued wisely, could represent a 'win-win-win' opportunity. But the promise of a lower-carbon transportation future can only be realised through federal and state policies that 'count carbs and make carbs count'.

## 26.4 Indirect land-use change impacts of biofuels

The indirect land use change impacts of biofuels, also known as ILUC, relates to the unintended consequence of releasing more carbon emissions due to land use changes around the world induced by the expansion of croplands for ethanol or biodiesel production in response to the increased global demand for biofuels. As farmers worldwide respond to higher crop prices in order to maintain the global food supply and demand balance, pristine lands are clear and converted to new cropland to replace the crops for feed and food that were diverted elsewhere to biofuels production. Because natural lands, such as rainforests and grasslands, store and sequester carbon in their soil and biomass as plants grow each year, clearance of wilderness for new farms in other regions or countries translates in a net increase in greenhouse gas emissions, and due to this change in the carbon stock of the soil and the biomass, indirect land use change has consequences in the GHG balance of a biofuel.

Other authors have also argued that indirect land use changes not only releases sequestered carbon, but also has other significant social and environmental impacts, putting pressure on biodiversity, soil, water quality, food prices and supply, concentration of land tenure, displacement of workers and local communities, and cultural disruption.

Until 2008 several full life-cycle studies had found that corn ethanol, cellulosic ethanol and Brazilian sugarcane ethanol reduce greenhouse gas emissions as compared to gasoline. The actual reduction estimates on carbon intensity for a given biofuel can be better or worse depending on the assumptions regarding several variables. Nevertheless, none of these studies considered the effects of indirect land-use changes, and though their impact was recognised, its estimation was considered too complex and more difficult to model than direct land use changes. A controversial paper published in February 2008 in Sciencexpress by a team led by Searchinger from Princeton University concluded that once considered indirect land use changes effects in the life-cycle assessment of biofuels used to substitute gasoline, instead of savings both corn and cellulosic ethanol increased carbon emissions as compared to gasoline, and only ethanol from Brazilian sugarcane performs better but still with a small carbon debt.

Since the publication of the Searchinger team paper, estimation of carbon emissions from ILUC, together with the food versus fuel debate, has become one of the most contentious issues relating to biofuels and it has been debated in the popular media, scientific journals, op-eds and public letters from members of the scientific community on both sides of the issue, and criticised by the ethanol industry, both American and Brazilian. This controversy was intensified in April 2009 when the California Air Resources Board (CARB) set rules that include ILUC impacts to establish the California Low-Carbon Fuel Standard that will enter into force in 2011. On May 2009 US Environmental Protection Agency (EPA) released a notice of proposed rulemaking for implementation of the 2007 modification of the Renewable Fuel Standard (RFS). The draft of the regulations was released for public comment during a 60-day period. EPA's proposed regulations are also including the carbon emissions resulting from indirect land use changes, causing additional controversy among ethanol producers.

The UK Renewable Transport Fuel Obligation program requires the Renewable Fuels Agency (RFA) to report any potential indirect impacts of biofuel production, including indirect land use change or changes to food and other commodity prices. A study published in July 2008 and conducted by RFA, known as the Gallager Review, concluded among other things, that there are several risks and uncertainties involved, and that the 'quantification of GHG emissions from indirect land use change requires subjective assumptions and contains considerable uncertainty', therefore, further examination is required to fully understand the implications of indirect effects in order to adequately incorporate ILUC and other indirect effects into calculation methodologies. A similar cautious approach was followed by the European Union. On December 2008 the European Parliament approved amendments to the directives regulating the use of biofuels and other renewable fuels for transport, to include more stringent sustainability criteria for biofuels and mandated to take into account indirect land use changes, even though it did not immediately adopted specific ILUC penalties, but rather ordered the European Commission to develop a methodology to factor in GHG emissions from indirect land use change.

## 26.5 Food versus fuel

Food versus fuel is the dilemma regarding the risk of diverting farmland or crops for biofuels production in detriment of the food supply on a global scale. The 'food versus fuel' or 'food or fuel' debate is international in scope, with good and valid arguments on all sides of this issue. The discussion in this chapter is only about using food crops for fuel and ignores methanol biofuels and the methanol economy. There is disagreement about how significant this is, what is causing it, what the impact is, and what can or should be done about it.

Biofuel production has increased in recent years. Some commodities like maize, sugar cane or vegetable oil can be used either as food, feed or to make biofuels. For example, since 2006, land that was also formerly used to grow other crops in the United States (US), Europe and developing countries are now used to grow maize for biofuels, and a larger share of maize is destined to ethanol production, reaching 25 per cent in 2007. Since converting the entire grain harvest of the US would only produce 16 per cent of its auto fuel needs, some experts believe that placing energy markets in competition with food markets for scarce arable land will inevitably result in higher food prices. A lot of R&D efforts are currently being put into the production of second generation biofuels from non-food crops, crop residues and waste. Second generation biofuels could hence potentially combine farming for food and fuel and moreover, electricity could be generated simultaneously, which could be beneficial for developing countries and rural areas in developed countries.

With global demand for biofuels on the increase due to the oil price increases taking place since 2003 and the desire to reduce oil dependency as well as reduce greenhouse gas (GHG) emissions from transportation, there is also fear of the potential destruction of natural habitats by being converted into farmland. Environmental groups have raised concerns about this trade-off for several years, but now the debate reached a global scale due to the 2007–2008 world food price crisis. On the other hand, several studies do show that biofuel production can be significantly increased without increased acreage. Therefore stating that the crisis in hand relies on the food scarcity.

Brazil has been considered to have the world's first sustainable biofuels economy and its government claims Brazil's sugarcane-based ethanol industry has not contributed to the 2008 food crisis. A World Bank policy research working paper released in July 2008 concluded that 'large increases in biofuels production in the United States and Europe are the main reason behind the steep rise in global food prices', and also stated that 'Brazil's sugar-based ethanol did not push food prices appreciably higher'.

### 26.5.1 Food price inflation

From 1974 to 2005 real food prices (adjusted for inflation) dropped by 75 per cent. Food commodity prices were relatively stable after reaching lows in 2000 and 2001. Therefore, recent rapid food price increases are considered extraordinary. A World Bank policy research working paper published on July

2008 found that the increase in food commodities prices was led by grains, with sharp price increases in 2005 despite record crops worldwide. From January 2005 until June 2008, maize prices almost tripled, wheat increased 127 per cent, and rice rose 170 per cent. The increase in grain prices was followed by increases in fats and oil prices in mid-2006. On the other hand, the study found that sugar cane production has increased rapidly, and it was large enough to keep sugar price increases small except for 2005 and early 2006. The paper concluded that biofuels produced from grains have raised food prices in combination with other related factors between 70 to 75 per cent, but ethanol produced from sugar cane has not contributed significantly to the recent increase in food commodities prices.

An economic assessment report published by the Organisation for Economic Co-operation and Development (OECD) in July 2008 found that ‘the impact of current biofuel policies on world crop prices, largely through increased demand for cereals and vegetable oils, is significant but should not be overestimated. Current biofuel support measures alone are estimated to increase average wheat prices by about 5 per cent, maize by around 7 per cent and vegetable oil by about 19 per cent over the next 10 years’. Corn is used to make ethanol and prices went up by a factor of three in less than 3 years (measured in US dollars). Reports in 2007 linked stories as diverse as food riots in Mexico due to rising prices of corn for tortillas, and reduced profits at Heineken the large international brewer, to the increasing use of corn (maize) grown in the US Midwest for ethanol production. (In the case of beer, the barley area was cut in order to increase corn production. Barley is not currently used to produce ethanol.) Wheat is up by almost a factor of 3 in 3 years, while soyabeans are up by a factor of 2 in 2 years (both measured in US dollars). As corn is commonly used as feed for livestock, higher corn prices lead to higher prices in ‘animal source foods’. Vegetable oil is used to make biodiesel and has about doubled in price in the last couple of years. The price is roughly tracking crude oil prices. The 2007–2008 world food price crisis is blamed partly on the increased demand for biofuels. Rice prices have gone up by a factor of 3 even though rice is not directly used in biofuels. The USDA expects the 2009/2010 wheat season to be a record crop and 8 per cent higher than the previous year. They also expect rice to have a record crop. Wheat prices have dropped from a high over $12/bushel in May 2008 to under $8/bushel in May. Rice has also dropped from its highs.

According to a new report from the World Bank, the production of biofuel is pushing up food prices. These conclusions were confirmed by the Union of Concerned Scientists in their September 2008 newsletter in which they remarked that the World Bank analysis ‘contradicts US Secretary of Agriculture Ed Schaffer’s assertion that biofuels account for only a small percentage of rising food prices’.

According to the October consumer price index released November 19, 2008, food prices continued to rise in October 2008 and were 6.3 per cent higher than October 2007. Since July 2008 fuel costs dropped by nearly 60 per cent.

### 26.5.2 Proposed causes

#### *Ethanol fuel as an oxygenate additive*

The demand for ethanol fuel produced from field corn was spurred in the US by the discovery that methyl tertiary butyl ether (MTBE) was contaminating groundwater. MTBE use as a oxygenate additive was widespread due to mandates of the Clean Air Act amendments of 1992 to reduce carbon monoxide emissions. As a result, by 2006 MTBE use in gasoline was banned in almost 20 states. There was also concern that widespread and costly litigation might be taken against the US gasoline suppliers, and a 2005 decision refusing legal protection for MTBE, opened a new market for ethanol fuel, the primary substitute for MTBE. At a time when corn prices were around US $2 a bushel, corn growers recognised the potential of this new market and delivered accordingly. This demand shift took place at a time when oil prices were already significantly rising.

#### *Other factors*

That food prices went up at the same time fuel prices went up is not surprising and should not be entirely blamed on biofuels. Energy costs are a significant cost for fertiliser, farming, and food distribution. Also, China and other countries have had significant increases in their imports as their economies have grown. Sugar is one of the main feedstocks for ethanol and prices are down from 2 years ago. Part of the food price increase for international food commodities measured in US dollars is due to the dollar being devalued. Protectionism is also an important contributor to price increases. 36 per cent of world grain goes as fodder to feed animals, rather than people.

Over long time periods population growth and climate change could cause food prices to go up. However, these factors have been around for many years and food prices have jumped up in the last 3 years, so their contribution to the current problem is minimal.

#### *Governments distorting food and fuel markets*

France, Germany, the United Kingdom and the United States governments have supported biofuels with tax breaks, mandated use, and subsidies. These policies have the unintended consequence of diverting resources from food production and leading to surging food prices and the potential destruction of natural habitats. Current government policies cause distortions of supply and demand.

Fuel for agricultural use often does not have fuel taxes (farmers get duty-free petrol or diesel fuel). Biofuels may have subsidies and low/no retail fuel taxes. Biofuels compete with retail gasoline and diesel prices which have substantial taxes included. The net result is that it is possible for a farmer to use more than a gallon of fuel to make a gallon of biofuel and still make a profit. Some argue that this is a bad distortion of the market. There have been thousands of scholarly papers analysing how much energy goes into making ethanol from corn and how that compares to the energy in the ethanol. Government distortions can make things happen that would not make sense in a free market.

A World Bank policy research working paper concluded that biofuels have raised food prices between 70 to 75 per cent. The 'month-by-month' five year analysis disputes that increases in global grain consumption and droughts were responsible for significant price increases, reporting that this had had only a marginal impact. Instead the report argues that the EU and US drive for biofuels has had by far the biggest impact on food supply and prices, as increased production of biofuels in the US and EU were supported by subsidies and tariffs on imports, and considers that without these policies, price increases would have been smaller.

This research also concluded that Brazil's sugarcane-based ethanol has not raised sugar prices significantly, and recommends removing tariffs on ethanol imports by both the US and EU, to allow more efficient producers such as Brazil and other developing countries, including many African countries, to produce ethanol profitably for export to meet the mandates in the EU and the US.

An economic assessment published by the OECD in July 2008 agrees with the World Bank report recommendations regarding the negative effects of subsidies and import tariffs, but found that the estimated impact of biofuels on food prices are much smaller. The OECD study found that trade restrictions, mainly through import tariffs, protect the domestic industry from foreign competitors but impose a cost burden on domestic biofuel users and limits alternative suppliers. The report is also critical of limited reduction of GHG emissions achieved from biofuels based on feedstocks used in Europe and North America, founding that the current biofuel support policies would reduce greenhouse gas emissions from transport fuel by no more than 0.8 per cent by 2015, while Brazilian ethanol from sugar cane reduces greenhouse gas emissions by at least 80 per cent compared to fossil fuels. The assessment calls for the need for more open markets in biofuels and feedstocks in order to improve efficiency and lower costs.

### *Oil price increases*

Oil price increases since 2003 resulted in increased demand for biofuels. Transforming vegetable oil into biodiesel is not very hard or costly so there is a profitable arbitrage situation if vegetable oil is much cheaper than diesel. Diesel is also made from crude oil, so vegetable oil prices are partially linked to crude oil prices. Farmers can switch to growing vegetable oil crops if those are more profitable than food crops. So all food prices are linked to vegetable oil prices, and in turn to crude oil prices. A World Bank study concluded that oil prices and a weak dollar explain 25–30 per cent of total price rise between January 2002 and June 2008.

Demand for oil is outstripping the supply of oil and oil depletion is expected to cause crude oil prices to go up over the next 50 years. Record oil prices are inflating food prices worldwide, including those crops that have no relation to biofuels, such as rice and fish.

In Germany and Canada it is now much cheaper to heat a house by burning grain than by using fuel derived from crude oil. With oil at $120/barrel a savings of a factor of 3 on heating costs is possible. When crude oil was at $25/barrel there was no economic incentive to switch to a grain fed heater.

From 1971 to 1973, around the time of the 1973 oil crisis, corn and wheat prices went up by a factor of 3. There was no significant biofuel usage at that time.

## 26.5.3 Proposed action

### *Freeze on first-generation biofuel production*

Environmental campaigner George Monbiot has argued for a 5-year freeze on biofuels while their impact on poor communities and the environment is assessed. It has been suggested that a problem with Monbiot's approach is that economic drivers may be required in order to push through the development of more sustainable second-generation biofuel processes: it is possible that these could be stalled if biofuel production decreases. Some environmentalists are suspicious that second-generation biofuels may not solve the problem of a potential clash with food as they also use significant agricultural resources such as water.

A recent UN report on biofuel also raises issues regarding food security and biofuel production. Jean Ziegler, then UN Special Rapporteur on food, concluded that while the argument for biofuels in terms of energy efficiency and climate change are legitimate, the effects for the world's hungry of transforming wheat and maize crops into biofuel are 'absolutely catastrophic', and terms such use of arable land a 'crime against humanity'. Ziegler also calls for a 5-year moratorium on biofuel production. Ziegler's proposal for a five-year ban was rejected by the UN Secretary Ban Ki-moon, who called for a comprehensive review of the policies on biofuels, and said that 'just criticising biofuel may not be a good solution'.

Food surpluses exist in many developed countries. For example, the UK wheat surplus was around 2 million tonnes in 2005. This surplus alone could produce sufficient bioethanol to replace around 2.5 per cent of the UK's petroleum consumption, without requiring any increase in wheat cultivation or reduction in food supply or exports. However, above a few per cent, there would be direct competition between first generation biofuel production and food production. This is one reason why many view second-generation biofuels as increasingly important.

## *Nonfood crops for biofuel*

There are different types of biofuels and different feedstocks for them, and it has been proposed that only nonfood crops be used for biofuel. This avoids direct competition for commodities like corn and edible vegetable oil. However, as long as farmers can make more money by switching to biofuels they will. The law of supply and demand predicts that if fewer farmers are producing food the price of food will rise.

Third generation biofuels (biofuel from algae) uses nonedible raw materials sources that can be used for biodiesel and bioethanol.

## *Biodiesel*

Soyabean oil, which only represents half of the domestic raw materials available for biodiesel production in the United States, is one of many raw materials that can be used to produce biodiesel.

Nonfood crops like camelina, jatropha, seashore mallow and mustard, used for biodiesel, can thrive on marginal agricultural land where many trees and crops won't grow, or would produce only slow growth yields. Camelina is virtually 100 per cent efficient. It can be harvested and crushed for oil and the remaining parts can be used to produce high quality omega-3 rich animal feed, fibreboard, and glycerine. Camelina does not take away from land currently being utilised for food production. Most camelina acres are grown in areas that were previously not utilised for farming. For example, areas that receive limited rainfall that cannot sustain corn or soyabeans without the addition of irrigation can grow camelina and add to their profitability.

Jatropha cultivation provides benefits for local communities: Cultivation and fruit picking by hand is labour-intensive and needs around one person per hectare. In parts of rural India and Africa this provides much-needed jobs—about 2,00,000 people worldwide now find employment through jatropha. Moreover, villagers often find that they can grow other crops in the shade of the trees. Their communities will avoid importing expensive diesel and there will be some for export too.

National Business Brokers (NBB's) Feedstock Development program is addressing production of arid variety crops, algae, waste greases, and other feedstocks on the horizon to expand available material for biodiesel in a sustainable manner.

### *Bioalcohols*

Cellulosic ethanol is a type of biofuel produced from lignocellulose, a material that comprises much of the mass of plants. Corn stover, switchgrass, miscanthus and woodchip are some of the more popular nonedible cellulosic materials for ethanol production. Commercial investment in such second-generation biofuels began in 2006/2007, and much of this investment went beyond pilot-scale plants. Cellulosic ethanol commercialisation is moving forward rapidly. The world's first commercial wood-to-ethanol plant began operation in Japan in 2007, with a capacity of 1.4 million litres/year. The first wood-to-ethanol plant in the United States is planned for 2008 with an initial output of 75 million litres/year.

Other second generation biofuels may be commercialised in the future and compete less with food. Synthetic fuel can be made from coal or biomass and may be commercialised soon.

### *Biofuel from food by-products and co-products*

Biofuels can also be produced from the waste by-products of food-based agriculture (such as citrus peels or used vegetable oil) to manufacture an environmentally sustainable fuel supply, and reduce waste disposal cost. A growing percentage of US biodiesel production is made from waste vegetable oil (recycled restaurant oils) and greases.

Collocation of a waste generator with a waste-to-ethanol plant can reduce the waste producer's operating cost, while creating a more-profitable ethanol production business. This innovative collocation concept is sometimes called holistic systems engineering. Collocation disposal elimination may be one of the few cost-effective, environmentally-sound, biofuel strategies, but its scalability is limited by availability of appropriate waste generation sources. For example, millions of tons of wet Florida-and-California citrus peels cannot supply billions of gallons of biofuels. Due to the higher cost of transporting ethanol, it is a local partial solution, at best.

More firms are investigating the potential of fractionating technology to remove corn germ (i.e. the portion of the corn kernel that contains oil) prior to the ethanol process. Furthermore, some ethanol plants have already announced their intention to employ technology to remove the remaining vegetable oil from dried distillers grains, a co-product of the ethanol process. Both of these technologies would add to the biodiesel raw material supply.

## *End unsustainable biofuel subsidies and tariffs*

Some people have claimed that ending subsidies and tariffs would enable sustainable development of a global biofuels market. Taxing biofuel imports while letting petroleum in duty-free does not fit with the goal of encouraging biofuels. Ending mandates, subsidies, and tariffs would end the distortions that current policy is causing. Some US senators advocate reducing subsidies for corn-based ethanol. The US ethanol tariff and some US ethanol subsidies are currently set to expire over the next couple of years. The EU is rethinking their biofuels directive due to environmental and social concerns. On January 18, 2008 the UK House of Commons Environmental Audit Committee raised similar concerns, and called for a moratorium on biofuel targets. Germany ended their subsidy of biodiesel on Jannuary 1, 2008 and started taxing it.

## *Reduce farmland reserves and set asides*

Some countries have programs to hold farmland fallow in reserve. The current crisis has prompted proposals to bring some of the reserve farmland back into use. The American Bakers Association has proposed reducing the amount of farmland held in the US Conservation Reserve Program. Currently the US has 3,45,00,000 acres (1,40,000 $km^2$) in the program. In Europe about 8 per cent of the farmland is in set aside programs. Farmers have proposed freeing up all of this for farming. Two-thirds of the farmers who were on these programs in the UK are not renewing when their term expires.

## *Sustainable production of biofuels*

Second generation biofuels are now being produced from the cellulose in dedicated energy crops (such as perennial grasses), forestry materials, the co-products from food production, and domestic vegetable waste. Advances in the conversion processes will almost certainly improve the sustainability of biofuels, through better efficiencies and reduced environmental impact of producing biofuels, from both existing food crops and from cellulosic sources.

Lord Ron Oxburgh suggests that responsible production of biofuels has several advantages:

Produced responsibly they are a sustainable energy source that need not divert any land from growing food nor damage the environment; they can also help solve the problems of the waste generated by Western society; and they can create jobs for the poor where previously were none. Produced irresponsibly, they at best offer no climate benefit and, at worst, have detrimental social and environmental consequences. In other words, biofuels are pretty much like any other product.

Far from creating food shortages, responsible production and distribution of biofuels represents the best opportunity for sustainable economic prospects in Africa, Latin America and impoverished Asia. Biofuels offer the prospect of real market competition and oil price moderation. According to the Wall Street Journal, crude oil would be trading 15 per cent higher and gasoline would be as much as 25 per cent more expensive, if it were not for biofuels. A healthy supply of alternative energy sources will help to combat gasoline price spikes.

### 26.5.4 Impact on developing countries

Demand for fuel in rich countries is now competing against demand for food in poor countries. Cars, not people, used most of the increase in world grain consumption in 2006. The grain required to fill a 25 gallon SUV gas tank with ethanol will feed one person for a year. Several factors combine to make recent grain and oilseed price increases impact poor countries more:

1. The World Bank estimated that in 2001 there were 2.7 billion people who lived in poverty on less than US$ (PPP) 2 per day. This was nearly half the 2001 world population of 6 billion.
2. While rich people buy processed and packaged foods like Wheaties, where prices don't change much if wheat prices go up, poor people buy more grains like wheat and feel the full impact of grain price changes.
3. Poor people spend a higher portion of their income on food, so higher food prices hurt them more, unless they are farmers. If a poor person spends 60 per cent of their money on food and then the food prices double, they will experience immediate hardship. So higher grain and oilseed prices will affect poorer countries more.
4. Aid organisations that buy food and send it to poor countries are only able to send half as much food on the same budget if prices double. But the higher prices mean there are more people in need of aid.

The impact is not all negative. The food and agriculture organisation (FAO) recognises the potential opportunities that the growing biofuel market offers to small farmers and aquaculturers around the world and has recommended small-scale financing to help farmers in poor countries produce local biofuel.

On the other hand, poor countries that do substantial farming have increased profits due to biofuels. If vegetable oil prices double, the profit margin could more than double. In the past rich countries have been dumping subsidised grains at below cost prices into poor countries and hurting the local farming industries. With biofuels using grains the rich countries no longer have grain surpluses to get rid of. Farming in poor countries is seeing healthier profit margins and expanding.

Interviews with local peasants in southern Ecuador provide strong anecdotal evidence that the high price of corn is encouraging the burning of tropical forests. The destruction of tropical forests now account for 20 per cent of all greenhouse gas emissions.

### 26.5.5 Controversy within the international system

The United States and Brazil lead the industrial world in global ethanol production, with Brazil as the world's largest exporter and biofuel industry leader. In 2006 the US produced 18.4 billion litres (4.86 billion gallons), closely followed by Brazil with 16.3 billion litres (4.3 billion gallons), producing together 70 per cent of the world's ethanol market and nearly 90 per cent of ethanol used as fuel. These countries are followed by China with 7.5 per cent, and India with 3.7 per cent of the global market share.

Since 2007, the concerns, criticisms and controversy surrounding the food versus biofuels issue has reached the international system, mainly heads of states, and inter-governmental organisations (IGOs), such as the United Nations and several of its agencies, particularly the Food and Agriculture Organisation (FAO) and the World Food Program (WFP); the International Monetary Fund; the World Bank; and agencies within the European Union.

The two countries also agreed to share technology and set international standards for biofuels. The Brazilian sugar cane technology transfer will permit various Central American countries, such as Honduras, Nicaragua, Costa Rica and Panama, several Caribbean countries, and various Andean countries tariff-free trade with the US thanks to existing concessionary trade agreements. Even though the US imposes a US $0.54 tariff on every gallon of imported ethanol, the Caribbean nations and countries in the Central American Free Trade Agreement are exempt from such duties if they produce ethanol from crops grown in their own countries. The expectation is that using Brazilian technology for refining sugarcane-based ethanol, such countries could become exporters to the United States in the short-term. In August 2007, Brazil's President toured Mexico and several countries in Central America and the Caribbean to promote Brazilian ethanol technology. This alliance between the US and Brazil generated some negative reactions.

As a result of the international community's concerns regarding the steep increase in food prices, on April 14, 2008, Jean Ziegler, the United Nations Special Rapporteur on the Right to Food, at the Thirtieth Regional Conference of the food and agriculture organisation (FAO) in Brasília, called biofuels a 'crime against humanity', a claim he had previously made in October 2007, when he called for a 5 year ban for the conversion of land for the production of biofuels. The previous day, at their Annual IMF and World Bank Group meeting at Washington, DC the World Bank's President, Robert Zoellick, stated that 'While many worry about filling their gas tanks, many others around the world are struggling to fill their stomachs. And it's getting more and more difficult every day.'

## 26.6 Biofuels: biodevastation, hunger and false carbon credits

The carbon footprint of alternative liquid fuels (biofuel)—such as ethanol distilled from corn and other biofuel made from inedible plants like switch-grass—has been debated for months in scientific, corporate, and environmental circles. Substantial controversy occurred following the Searchinger, and Farigone, articles in the February 8, 2008, issue of Science, over the carbon impacts of indirect land use associated with biofuel production. These articles and others have highlighted the need to establish systems to measure US progress re: the Renewable Fuels Standard (RFS) of the Energy Independence and Security Act of 2007 which requires a 20 per cent carbon reduction from corn ethanol and a 50 per cent reduction from next generation cellulosic ethanol to meet the RFS. Further, it is widely anticipated that the Obama administration will implement a broader US carbon policy which will create more far reaching challenges in the near future. Governments in other countries are also struggling to formulate carbon accounting systems and policies that will encourage the substitution of alternative liquid fuels that significantly lower fuel carbon emissions.

Europe's thirst for biofuels is fuelling deforestation and food price hikes, exacerbated by a false accounting system that awards carbon credits to the carbon profligate nations. A mandatory certification scheme for biofuels is needed to protect the earth's most sensitive forest ecosystems, to stabilise climate and to safeguard our food security.

### 26.6.1 Biofuels not necessarily carbon neutral nor sustainable

Biofuels are fuels derived from crop plants, and include biomass directly burnt, and especially biodiesel from plant seed-oil, and bioethanol from fermenting grain, sap, grass, straw or wood. Biofuels have been promoted and mistakenly perceived to be 'carbon neutral', that they do not add any greenhouse gas to the atmosphere; burning them simply returns to the atmosphere the carbon dioxide that the plants take out when they were growing in the field.

This ignores the costs in carbon emissions and energy of the fertiliser and pesticides used for growing the crops, of farming implements, processing and refining, refinery plants, transport, and infrastructure for transport and distribution. The extra costs in energy and carbon emissions can be quite substantial particularly if the biofuels are made in one country and exported to another, or worse, if the raw materials, such as seed oils, are produced in one country to be refined for use in another. Both are very likely if current trends continue.

### 26.6.2 Growing demand for biofuels

Demand for biofuels has been growing as the world is running short of fossil fuels. Oil and gas prices have shot up within the past several years, while the pressure to reduce carbon emissions to mitigate global warming is increasingly pointing to biofuels as one of the main solutions. George W. Bush has offered biofuels to cure his country's addiction to oil. A 'billion ton vision' was unveiled to make available 1.3 billion tons of dry biomass for the biofuels industry by the middle of this century, to provide 30 per cent of US fuel use, if all things work out, such as a fifty per cent increase in crop yield. Biofuels Corporation plc, the first 2,50,000 MT biodiesel processing plant in the UK was opened by Tony Blair at the end of June 2006, and it will be using imported castor oil and palm oil as well as home grown rapeseed oil to make biodiesel. But UK lags far behind other European Union (EU) countries in biofuel use.

### 26.6.3 EU biofuels directive driving the industry in Third World countries

The European Union adopted a Biofuels Directive in May 2003 to promote the use of biofuels in transport at 5.75 per cent of market share by 2010, increasing to 8 per cent by 2015. These targets are not likely to be met on current projections. The market share for EU25 is 1.4 per cent; Austria leads at 2.5 per cent, while UK's share is a mere 0.2 per cent.

The European Commission is to make a progress report before the end of 2006; it has put out a document for public consultation, which ended in July 2006. Among the issues considered was the need for a biofuels certification scheme based on standards of sustainability.

EU countries are already growing bioenergy crops, mainly oil seed rape; and tax relief and incentives are granted for biofuels in ten or more countries. The 'set-aside' agricultural land meant to protect and conserve biodiversity is likely to be brought back into agriculture to grow bioenergy crops.

A report published in 2002 by the CONCAWE group—the oil companies' European association for environment, health and safety in refining and distribution—estimated that if all 5.6 million hectares of set-asides in the EU15 nations were intensively farmed for bioenergy crops, we could save merely 1.3–1.5 per cent of road transport emissions, or around 0.3 per cent of total emissions from those 15 countries.

These and other similarly pessimistic estimates are fuelling the growth in biofuels industries in Third World countries, where, we are now told, there is plenty of 'spare' land for growing bioenergy crops. The sunshine is brighter all year round, so crops grow faster, yield more and labour is cheap.

In the case of GM crops, however, we are told there is not enough land, and we need GM crops to boost yields to feed the world. GM crops have failed to boost yields so far, and are overwhelmingly rejected worldwide, especially in African countries where GM food and feed are being dumped as 'food aid'. Biotech companies are already promoting GM crops as bioenergy crops and hoping for less regulation and more public acceptance, as they won't be used as food or feed. But that will leave our ecosystem and food crops wide open to contamination by GM crops that are far from safe. The United Kingdom Energy Research Centre, which consists of members from all the government research councils, has already included 'public perception and use of GM technologies for bioenergy' in its 'Short term Research Challenge'.

### 26.6.4 Deforestation, species extinction and food price hikes

Biofuels are bad news, especially for poor Third World countries. Bioenergy crops do take up valuable land that could be used for growing food, and food security is becoming a burning issue. World grain yield has fallen for six of the past seven years, bringing reserves to the lowest in more than thirty years. Chronic depletion of aquifers in the major bread baskets of the world, drought and soaring temperatures are taking their toll and set to do even more damage to food production. The pressure on land from food and bioenergy crops will certainly speed up deforestation and species extinction, and at the same time result in food price increases worldwide, hitting the poorest, hungriest countries the hardest.

### 26.6.5 There is no spare land for energy crops

Calculations based on the best-case scenario of unrealistically high crop yields and high recovery of biofuels from processing still end up requiring 121 per cent of all the farmland in the United States to grow enough biomass to substitute for the fossil fuels consumed each year.

The EU's own technical report published in 2004 shows that the target of 5.75 per cent biofuel substitution for fossil fuels will require at least 14 to 19 per cent of farmland to grow bioenergy crops. There will be no set-aside land left to protect natural biodiversity, as that's only 12 per cent of farmland in the EU. Satellite data reveal that 40 per cent of the earth's land is already used up for agriculture, either growing crops or for pasture. There is no spare land for growing food, let alone bioenergy crops.

### 26.6.6 Deforestation speed-up in tropical Brazil, Malaysia and Indonesia

Tropical forests are the richest carbon stocks and the most effective carbon sinks the world. Estimates run as high as 418 T C/Ha in carbon stock, and 5 to 10 T C/Ha a year sequestered, forty per cent of which is in soil organic carbon. The carbon stock in old growth forests would be even greater, and according to a new study in Southeast China, soil organic carbon just in the top 20 centimetres of such old growth forests increased on average at a rate of 0.62 T C/Ha each year between 1979 and 2003. When tropical forests are cut down at the rate of more than 14 million Ha a year, some 5.8 Gt C is released to the atmosphere, only a fraction of which would be sequestered back in plantations. The additional pressure on land from bioenergy crops will mean yet more deforestation and a greater acceleration of global warming and species extinction. Vast swathes of the Amazon forest in Brazil have already been cleared for soyabean cultivation to feed the meat industry so far. Adding soyabean biodiesel to the requirement may cause the entire forest to die back. At the same time, sugarcane plantations that feed the country's huge bioethanol industry also encroaches on the Amazon, but far more so on the Atlantic forest and the Cerrado, a very bio-diverse grassland ecosystem, two-thirds of which are already destroyed or degraded.

The pressure on the forests in Malaysia and Indonesia is even more devastating. A Friends of the Earth Report, The Oil for Ape Scandal reveals that between 1985 and 2000 the development of oil-palm plantations was responsible for an estimated 87 per cent of deforestation in Malaysia. In Sumatra and Borneo, 4 million Ha of forests were lost to palm farms; and a further 6 million Ha are scheduled for clearance in Malaysia and 16.5 million

Ha in Indonesia. Palm oil is now referred to as ‘deforestation diesel’ as palm oil production in Indonesia and Malaysia is projected to rise dramatically in the biofuels fever. Palm oil is already widely used in the food and cosmetic industry, having replaced soya as the world’s leading edible oil. And as petrol and gas prices have gone through the roof, oil palm is finding its place as the major bioenergy crop. With yields of 5 tons (or 6000 litres) of crude oil per ha a year, oil palm produces more by a long shot than any other oil crop; for example, soyabeans and corn generate only 446 and 172 litres per Ha a year. Current global palm oil production of more than 28 million tons per year is set to double by 2020. Malaysia, the world’s leading producer and exporter of palm oil, is making it mandatory for diesel to contain five per cent palm oil by 2010, while Indonesia plans to halve its national consumption of petroleum by 2025 through substitution with biofuels. Malaysia and Indonesia have announced a joint commitment to each produce 6 million tons of crude palm oil per year to feed the production of biofuels.

### 26.6.7 Food price hikes as more diverted into biofuels

Demand for biofuels has turned traditional food crops into ‘bioenergy’ crops. Food and energy now compete for the same ‘feedstock’, with the result that food prices have gone up substantially, over and above the price of petroleum and natural gas that normally goes into producing food. By 2006, around 60 per cent of the total rapeseed oil produced in the EU has gone into making biodiesel. The price of rapeseed oil went up by 45 per cent in 2005, and then an additional 30 per cent to about US $800 per tons. Food giant Unilever estimated a further price increase of some 200 Euros per ton for next year due to additional biodiesel demand. The total additional cost to food manufacturers from biodiesel is estimated to be close to one thousand Euros by 2007.

Cereals prices have shot up. US corn prices have increased by more than 50 per cent since September 2006, and has now hit a 10-year high at US$3.77 a bushel. US demand for bioethanol has diverted corn from exports, leaving Asia corn buyers desperate. World wheat prices also hit a 10-year high of US $300 a ton in October 2006, amid fears of a supply crisis within the next 12 months if there is another disappointing year of global production. Another concern is the rising demand for biofuels to be created from crops such as wheat, corn and soya.

### 26.6.8 Other environmental concerns

Bioenergy crops deplete soil minerals and reduce soil fertility especially in the long-term, making the soil unsuitable for growing food. The processing wastes from all biofuels have substantial negative impacts on the environment, which have yet to be properly assessed and taken into account. Although some biodiesel may be cleaner than diesel, others are not. Burning bioethanol generates mutagens and carcinogens and increases ozone levels in the atmosphere.

### 26.6.9 Energy balance and carbon savings unfavourable on the whole

Biofuels are rated on energy and carbon in many different ways that are not completely transparent. The ones that are used as defined are energy balance, the units of biofuel energy produced per unit of input energy; and carbon saving, the percentage of greenhouse gas emissions prevented by producing and using the biofuel instead of producing and using the same amount of fossil fuel energy.

Biofuels generally give small to negative energy balance on a life-cycle analysis, in fact, mostly negative energy balance when proper accounting is done, which means that the energy in the biofuel is less than the sum of the energy spent in making it. It is likely that carbon savings will be equally unfavourable when all the costs are included.

Currently, most energy audits that give positive energy balance include energy content of by-products, such as the seedcake residue left over when oil has been extracted, that can be used as animal feed (though it is by no means so used as a rule), and fail to include infrastructure investments, such as the energy and carbon costs of building refinery plants, and roads and depots needed for transport and distribution; and certainly not the costs of exporting to another country. None of the audits includes environmental impacts. In the only case analysed by researchers at the Flemish Institute for Technological Research, sponsored by the Belgian Office for Scientific, Technical, and Cultural Affairs and the European Commission, it found that, ‘biodiesel fuel causes more health and environmental problems because it created more particulate pollution, released more pollutants that promote ozone formation, generated more waste and caused more eutrophication’.

A compilation of energy balance and carbon saving estimates is given in Table 26.1. Sugarcane bioethanol in Brazil is estimated to have an energy balance of a staggering 8.3 on average, and up to 10.2 in the best case; far ahead of any other biofuel, especially those produced in temperate regions, estimates for which range from a high of 2.2 to well below 1, a negative energy balance. The carbon saving of Brazilian sugarcane bioethanol at between 85 and 90 per cent, is also bigger by far than any other biofuel, which ranges from just over 50 per cent to –30 per cent, i.e. the biofuel incurs 30 per cent more greenhouse gas emissions to produce and use than the energy equivalent in fossil fuel.

**Table 26.1** Energy balance and carbon saving of biodiesel and bioethanol.

| Biodiesel | Energy balance | C saving |
|---|---|---|
| OSR (EU) | 1.59 | 52% |
| OSR (UK) | 1.78 | – |
| OSR (Australia) | – | 50% |
| Soya (USDoE) | 2.22 | 40% |
| Soya (US) | 0.53* | – |
| Bioethanol | | |
| Wheat and sugarbeet (EU) | 1.08 | 27% |
| Corn (US) | 1.13–1.34 | 13% |
| Maize (N France) | 1.03 | 24% |
| Sugarbeet (EU) | 1.18 | – |
| Wood (US) | 0.64 | – |
| Wood (Scand) | 0.80 | – |
| Sugarcane (Brazil) | 8.30–10.20 | 85–90% |

*Includes infrastructure costs and excludes by-products.

With two exceptions, all estimates include energy in by-products and exclude infrastructure costs. None include environmental damages or depletion of soil or costs of export to another country. As can be seen, with the possible exception of Brazilian sugarcane bioethanol, none of the bioenergy sources gives good enough returns on investments in energy and carbon emissions, even with the best gloss put on. When realistic accounting is done, they could all result in negative energy balance and carbon saving.

There are features that account for the relative success of sugarcane bioethanol. Apart from the prolific growth rate of the crop in tropical Brazil, the production involves a closed cycle, where the energy for the refinery and distillery process comes from burning sugarcane residue; hence no fossil fuels are needed. Refining and distillation are very energy intensive especially for bioethanol. The large energy balance will be reduced substantially when infrastructure and export costs are included, though it could still be positive. But even with the positive energy and carbon accounting, there are serious doubts that sugarcane bioethanol is sustainable. Among the main concerns are ecological and social impacts, including food security. These are especially important in a country where human rights and land rights are very problematic.

There is a lot of false accounting that inflates carbon savings. For example, the huge loss of soil organic carbon due to intensive sugarcane cultivation replacing forests and pastureland has not been taken in account, nor the fact that natural forests allowed to regenerate would save 7 T more carbon dioxide per Ha each year than that saved by the bioethanol from a ha of sugarcane and these are not the only forms of false accounting.

### 26.6.10 False carbon credits in southern Africa's jatropha biodiesel

Under international rules, none of the greenhouse gas linked to the production of biofuels will be attributed to the transport sector. The emission that arise during biofuel production will be counted towards agricultural and industry and/or energy sector emissions. Also, all the emissions that come from growing and refining in Third World countries, will count towards those countries' emissions, so a country importing the biofuel such as the UK can use them to improve its greenhouse gas inventory. This allows rich importing nations to outsource some of their emissions and claim credit for doing so under the Kyoto Agreement. This is how plantations of jatropha trees have become established in Malawi and Zambia. Jatropha is a drought resistant plant that requires little or no input of pesticides or fertilisers. Jatropha beans can be harvested 3 times a year, and the by-products can be used to make soap and even medicine. Refining is done in South Africa. Many farmers switched from tobacco to Jatropha, which is considered a good thing, as tobacco is a very environmentally unfriendly plant to grow. So far there are 2,00,000 Ha of jatropha in Malawi and 15,000 Ha in Zambia, almost all under a formal lease or agreements with the UK-based company D1-oils.

Southern Africa is one of the most vulnerable regions in the world to climate change. All climate models predict that the region (not including most of South Africa, Lesotho and Swaziland) will become a lot warmer and drier, with more frequent and severe droughts, interspersed by more severe flooding. This could cause massive crop failures and a collapse of food production.

About 80 per cent of Zambia's population rely on biomass for all or most of their energy needs, with only 12 per cent having access to electricity. In Malawi, 90 per cent of primary energy production comes from biomass, i.e. firewood and charcoal. Most rural people rely on burning firewood, often on inefficient cooking stoves, which causes serious pollution and are a major cause of ill health and death. Women and girls are particularly affected.

Jatropha plantations may have serious impacts on the food and energy security of the region, especially if they expand. So far, there has been no life-cycle analysis or sustainability study on jatropha biofuel.

### 26.6.11 Transparent life-cycle auditing, environmental impact assessment and a mandatory certification scheme needed now

It is quite clear that biofuels currently come in many different forms, most of which are not carbon neutral. There is an urgent need for transparent life-cycle auditing of energy and carbon emissions and other sustainability criteria involving impacts on health, environment and social welfare. Many have called for a mandatory certification scheme based on clear criteria of sustainability that safeguard the world's most sensitive forest ecosystems as well as the long-term fertility of our land and soil. These criteria should also guarantee food sovereignty (the right to be secure in food supply of people's own choice) and related land and labour rights to all.

We have many renewable and truly sustainable alternatives to the current biofuels. It is suggested/proposed to assemble these options in a zero-emission, zero-waste food and energy. One of the core technology used is anaerobic digestion, which turns wastes (and environmental pollutants) into crop and livestock nutrients and energy in the form of biogas, consisting of 60 per cent or more methane, which can be used to power cars as well as for generating electricity.

It is estimated that if all the biological and livestock wastes in Britain were treated in anaerobic digesters, it would supply more than half the country's transport fuel. Admittedly, the vehicles will need a different engine, but such cars are already on the market, and biogas methane-driven cars have exhausts so clean that they were voted environmental cars of the year in 2005.

# Glossary

| | | |
|---|---|---|
| *Activated sludge* | : | Biological waste-water treatment process in which a mixture of the waste-*process* water and activated sludge is aerated in a reactor basin or aeration tank. Activebiological solids bio-oxidise the waste matter and the biological solids are removed by secondary clarification or final settling. |
| *Aerated lagoon* | : | Waste-water treatment pond in which mechanical or diffused air aeration is used to supplement oxygen supply. |
| *Aerobic digestion* | : | Digestion of suspended organic matter by aerobic microbes. |
| *Algae* | : | Primitive plant-like organisms, single or multicellular, usually aquatic andcapable of utilising food materials through photosynthesis. |
| *Algae blooms* | : | Elevated growth of one or more species of algae, which may result from excessive nutrient loading, in combination with adequate light, temperature and other environmental factors. |
| *Alternating current* | : | An electric current changing regularly from one direction to the opposite. |
| *Anaerobic* | : | Requiring combined oxygen, such as $SO_4^{-2}$, $PO_4^{-3}$, $NO_3^{-1}$ and the absence of free molecular oxygen. |
| *Anaerobic bacteria* | : | Bacteria that require combined oxygen and the absence of free molecular oxygen. |
| *Anaerobic digestion* | : | Digestion of suspended organic matter by anaerobic microbial action. |
| *Aquaculture* | : | Farming of organisms that live in water, such as fish, shellfish, and algae. |
| *Auxiliary heat source* | : | Source of heat, other than solar, used to supplement the output provided by the solar heating system. |
| *Baseload* | : | The minimum constant amount of load connected to the power system over a given time period, usually on a monthly, seasonal or yearly basis. |

*Baseload plant* : A plant, usually housing high-efficiency steam-electric units, which is normally operated to take all or part of the minimum load of a system, and which consequently produces electricity at an essentially constant rate and runs continuously. These units are operated to maximise system mechanical and thermal efficiency and minimise system operating costs.

*Binary-cycle plant* : A geothermal electricity generating plant employing a closed-loop heat exchange system in which the heat of the geothermal fluid (the 'primary fluid') is transferred to a lower-boiling-point fluid (the 'secondary' or 'working' fluid), which is thereby vapourised and used to drive a turbine/generator set.

*Biochemical oxidation* : Oxidation caused by biological activity resulting in a chemical combinationof oxygen with organic matter to produce relatively stable end-products.

*Biochemical oxygen demand* : Oxygen required by microbes in the stabilisation of a decomposable waste under aerobic conditions.

*Biodegradation* : Biological oxidation of natural or synthetic organic materials by soil micro-organisms, either in soils, water bodies or waste-water treatment plants.

*Biofuels* : Wood, waste, and alcohol fuels.

*Biomass* : Living or recently living biological matter that can be used as a fuel. Biomass usually refers to plant matter but can also refer to animal or waste materials.

*Biotic* : Pertains to living organisms.

*Brine* : A geothermal solution containing appreciable amounts of sodium chloride or other salts.

*Btu (British Thermal Unit)* : A standard unit for measuring the quantity of heat energy equal to the quantity of heat required to raise the temperature of 1 pound of water by 1°F.

*Bus (buswork)* : A conductor or group of conductors, that serve as a common connection for two or more electrical circuits. In powerplants, buswork comprises the three rigid single-phase connectors that interconnect the generator and the step-up transformer(s).

*Capacity* : The amount of electric power delivered or required for which a generator, turbine, transformer, transmission circuit, station or system is rated by the manufacturer.

*Chemical coagulation* : The destabilisation and initial aggregation of colloidal and finely suspendedmatter by the addition of a floc-forming chemical coagulant.

*Chemical oxygen demand (COD)* : The amount of oxygen required to chemically oxidise the organic and sometimes inorganic matter in a water or waste-water. Usually expressed in mg/l. COD test does not measure the oxygen required to convert ammonia to nitrites and nitrites to nitrates, COD is frequently assumed to be equal to the ultimate first-stage biochemical oxygen demand.

*Chemical sludge* : Sludge produced by chemical coagulation or chemical precipitation.

*Chemically treated secondary effluent* : Secondary effluent that has been chemically treated, usually by coagulation, along with other processes or operations.

*Coagulant* : A compound that causes coagulation or a floc-forming agent.

*Coagulation* : In water or waste-water treatment, the destabilisation and initial aggregation of colloidal and finely divided suspended solids by the addition of floc-forming chemicals.

*Combined cycle* : An electric generating technology in which electricity is produced from otherwise lost waste heat exiting from one or more gas (combustion) turbines. The exiting heat is routed to a conventional boiler or to a heat recovery steam generator for utilisation by a steam turbine in the production of electricity. This process increases the efficiency of the electric generating unit.

*Condensate* : Water formed by condensation of steam.

*Conventional activated sludge process* : Activated sludge plant with rectangular reactor basin and air diffusers or aerators spaced uniformly along the basin length.

*Conventional digester* : A low-rate anaerobic digester.

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| *Conventional waste-water treatment* | : | Use of primary and secondary treatment. |
| *Conversion technology* | : | Represents the entire process of turning hydrothermal fluids or steam into electricity. |
| *Corrosion* | : | A state of deterioration in metals caused by oxidation or chemical action. |
| *Crust* | : | Earth's outer layer of rock. Also called the lithosphere. |
| *Dam* | : | A massive wall or structure built across a valley or river for storing water. |
| *Decomposition of waste-water* | : | Breakdown of organic matter in waste-water by microbial action. It may be under aerobic or anaerobic conditions. |
| *Degradation* | : | Breakdown of substances by biological oxidation. |
| *Demand (utility)* | : | The level at which electricity or natural gas is delivered to users at a given point in time. Electric demand is expressed in kilowatts. |
| *Deposition* | : | Deposition is the settling of particles (atoms or molecules) or sediment from a solution or suspension mixture or the production of a solid on a pre-existing surface. It is also known by the particle model of matter as the process of gas changing form directly to a solid. |
| *Disinfection* | : | The killing or inactivation of most of the micro-organisms in or on a substancewith the probability that all pathogenic bacteria are killed by the disinfecting agent used. |
| *Dissolved oxygen* | : | Oxygen dissolved in a liquid, usually expressed in mg/l. Abbreviated as DO. |
| *Dissolved solids* | : | Materials that enter a water body in a solid phase and dissolve in water. |
| *Distribution system* | : | The portion of an electric system that is dedicated to delivering electric energy to an end user. The distribution system 'steps down' power from high-voltage transmission lines to a level that can be used in homes and businesses. |
| *Drilling* | : | Boring into the earth to access geothermal resources, usually with oil and gas drilling equipment that has been modified to meet geothermal requirements. |

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| *Effluent* | : Waste-water of other liquid, partially or completely treated, or in its natural state, flowing out of a basin, reservoir, treatment plant or industrial treatment plant or parts thereof. |
| *Energy* | : The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatt-hours, while heat energy is usually measured in British thermal units. |
| *Energy efficiency* | : Refers to programs that are aimed at reducing the energy used by specific end-use devices and systems, typically without affecting the services provided. These programs reduce overall electricity consumption (reported in megawatt-hours), often without explicit consideration for the timing of program-induced savings. Such savings are generally achieved by substituting technically more advanced equipment to produce the same level of end-use services (e.g. lighting, heating, motor drive) with less electricity. Examples include high-efficiency appliances, efficient lighting programs, high-efficiency heating, ventilating and air conditioning (HVAC) systems or control modifications, efficient building design, advanced electric motor drives, and heat recovery systems. |
| *Energy source* | : The primary source that provides the power that is converted to electricity through chemical, mechanical, or other means. Energy sources include coal, petroleum and petroleum products, gas, water, uranium, wind, sunlight, geothermal, and other sources. |
| *Enthalpy* | : A thermodynamic quantity equal to the internal energy of a system plus the product of its volume and pressure; 'enthalpy is the amount of energy in a system capable of doing mechanical work'. |

*Enzymes* : Organic catalysts that are proteins and are produced by living cells.

*Escherichia coli (E. coli)* : A species of bacteria in the coliform group. Its presence is considered indicative of fresh fecal contamination.

*Filter* : Structure with a granular-bed and underdrain system that is used to remove fine suspended solids and colloids from a water or waste-water. The separation occurs as the liquid passes through the bed.

*Final effluent* : Effluent from the final clarifier, final sedimentation basin, or final settlingtank at a waste-water treatment plant.

*First-stage biochemical oxygen demand* : That part of the biochemical oxygen demand that results from the biological oxidation of carbonaceous materials, as distinct from nitrogenous materials. Generally, the major portion of carbonaceous materials are bio-oxidised before the bio-oxidation of nitrogenous materials, or the second-stage biochemical oxygen, demand begins.

*Five-day biochemical oxygen demand (BOD5)* : Oxygen required by microbes in the stabilisation of a decomposable waste under aerobic conditions for a period of five days at 20°C and under specified conditions. It represents the breakdown of carbonaceous materials as distinct from nitrogenous materials.

*Flash steam* : Steam produced when the pressure on a geothermal liquid is reduced. Also called flashing.

*Flocculation* : Slow stirring of a coagulated water or waste-water to aggregate the destabilised particles and form a rapid-settling floc. In biological waste-water treatment where a coagulant is not used, aggregation may be accomplished biologically.

*Fluidised bed* : Refers to a bed in which the particles are not in continuous contact due to the upward flow of the water or waste-water.

*Forced-circulation system* : A solar heating system which utilises a pump or a fan to circulate the heat transfer fluid through the collector(s).

*Fossil fuel* : Any naturally occurring organic fuel, such as petroleum, coal, and natural gas.

*Fossil-fuel plant* : A plant using coal, petroleum or gas as its source of energy.

*Fuel* : Any substance that can be burned to produce heat; also, materials that can be fissioned in a chain reaction to produce heat.

*Fungi* : Small, multicellular, non-photosynthetic, plant-like organisms lacking chlorophyll, roots, stems, or leaves that feed on organic matter. Their decomposition after death may cause disagreeable tastes and odours in a water. They are found in water, waste-water, waste-water effluents and soil.

*Gasification* : Conversion of soluble organic matter into gas during anaerobic bio-oxidation.

*Generating unit* : Any combination of physically connected generator(s), reactor(s), boiler(s), combustion turbine(s) or other prime mover(s) operated together to produce electric power.

*Generator* : A machine that converts mechanical power into electricity by spinning copper wires (conductors) within a magnetic field.

*Geothermal energy* : Natural heat from within the earth, captured for production of electric power, space heating or industrial steam.

*Geothermal heat pumps* : Devices that take advantage of the relatively constant temperature of the earth's interior, using it as a source and sink of heat for both heating and cooling. When cooling, heat is extracted from the space and dissipated into the earth; when heating, heat is extracted from the earth and pumped into the space.

*Geothermal plant* : A plant in which the prime mover is a steam turbine. The turbine is driven either by steam produced from hot water or by natural steam that derives its energy from heat found in rocks or fluids at various depths beneath the surface of the earth. The energy is extracted by drilling and/or pumping.

*Geothermal steam* : Steam drawn from deep within the earth.

*Geyser* : A spring that shoots jets of hot water and steam into the air.

*Greenhouse effect* : The increasing mean global surface temperature of the earth caused by gases in the atmosphere (including carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbon). The greenhouse effect allows solar radiation to penetrate but absorbs the infrared radiation returning to space.

*Grid* : The layout of an electrical distribution system.

*Hazardous waste* : Unwanted by-products remaining in the environment and posing an immediate potential hazard to human life.

*Hydrocarbon* : An organic compound containing only carbon and hydrogen. Hydrocarbons often occur in petroleum products, natural gas, and coals.

*Hydroelectric power* : Electric current produced from water power.

*Hydroelectric powerplant* : A building in which turbines are operated, to drive generators, by the energy of natural or artificial waterfalls.

*Hydrogen sulphide* : Gas emitted during organic decomposition. Also a by-product of oil refining and burning. Smells like rotten eggs and, in heavy concentration, can kill or cause illness.

*Irradiance* : Power density of radiation incident on a surface, i.e. the quotient of the radiant flux incident on the surface and the area of that surface or the rate at which radiant energy is incident on a surface, per unit area of that surface. Irradiance is normally expressed in watts per square meter ($W/m^2$).

*Kilowatt (kW)* : Unit of electric power equal to 1000 watts or about 1.34 horsepower. For example, it is the amount of electric energy required to light ten 100-watt light bulbs.

*Kilowatt-hour (kWh)* : The unit of electrical energy commonly used in marketing electric power; the energy produced by 1 kilowatt acting for one hour. Ten 100-watt light bulbs burning for one hour would consume one kilowatt hour of electricity.

*Kinetic energy* : Energy which a moving body has because of its motion, dependent on its mass and the rate at which it is moving.

*Magma* : The molten rock and elements that lie below the earth's crust. The heat energy can approach 1000°F (538°C) and is generated directly from a shallow molten magma resource and stored in adjacent rock structures. To extract energy from magma resources requires drilling near or directly into a magma chamber and circulating water down the well in a convection type system.

*Mantle* : The earth's inner layer of molten rock, lying beneath the earth's crust and above the earth's core of liquid iron and nickel.

*Microbial activity* : Chemical changes resulting from biochemical action, the metabolism of living organisms.

*Micro-organism* : Minute organisms, some being plant-like or animal-like, visible only by means of a microscope; microbe.

*Particulate matter (PM)* : Unburned fuel particles that form smoke or soot and stick to lung tissue when inhaled. A chief component of exhaust emissions from heavy-duty diesel engines.

*Peakload* : The greatest amount of power given out or taken in by a machine or power distribution system in a given time.

*Photosynthesis* : Synthesis of complex organic materials from carbon dioxide, water and inorganic salts using sunlight as the energy source and a catalyst such as chlorophyll.

*Plain sedimentation* : Gravity settling of suspended solids in a water or waste-water without the aid of chemical coagulants.

*Pollution* : Unwanted particles, mist or gases put into the atmosphere as a result of motor vehicle exhaust, the operation of industrial facilities or other human activity.

*Power* : The rate at which energy is transferred. Electrical energy is usually measured in watts. Also used for a measurement of capacity.

*Power plant* : A central station generating facility that produces energy.

*Preliminary treatment* : In a waste-water treatment plant, this refers to unit operations such as screening, comminution or grit removal that prepare the waste-water for subsequent major operations.

*Production well* : A production well is a well drilled through a geothermal resource that produces geothermal brine.

*Pumped-storage hydroelectric plant* : A plant that usually generates electric energy during peak-load periods by using water previously pumped into an elevated storage reservoir during off-peak periods when excess generating capacity is available to do so. When additional generating capacity is needed, the water can be released from the reservoir through a conduit to turbine generators located in a power plant at a lower level.

*Rankine cycle* : The thermodynamic cycle that is an ideal standard for comparing performance of heat-engines, steam power plants, steam turbines, and heat pump systems that use a condensable vapour as the working fluid; efficiency is measured as work done divided by sensible heat supplied.

*Renewable energy* : Resources that constantly renew themselves or that are regarded as practically inexhaustible. These include solar, wind, geothermal, hydro and wood. Although particular geothermal formations can be depleted, the natural heat in the earth is a virtually inexhaustible reserve of potential energy. Renewable resources also include some experimental or less-developed sources such as tidal power, sea currents and ocean thermal gradients.

*Reservoir* : A natural underground container of liquids, such as water or steam (or in the petroleum context, oil or gas).

*Revegetation* : Regrowing native plants, mainly trees and shrubs, by active restoration, natural process restoration or both.

*Reverse osmosis* : A type of pressurised filtration system in which water is forced through a semipermeable membrane that allows the passage of water but restricts many contaminants.

*Sanitary landfill* : Landfill for disposing of solid wastes.

*Sanitary waste-water* : Domestic waste-water without storm and surface runoff. Waste-water from thesanitary conveniences in dwellings, office buildings, industrial plants andinstitutions. Water supply of a community after it has been used and discharged to a sewer.

*Scrubber* : Equipment used to remove sulphur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Chemicals, such as lime, are used as the scrubbing media.

*Secondary effluent* : Effluent leaving the secondary or final clarifier at a waste-water treatment plant.

*Secondary sludge* : Sludge from the final clarifier at waste-water treatment plant. For the activatedsludge process, it is the sludge to be recycled. For the trickling filter process, it is the trickle filter growths that have sloughed off—that is, the trickling filter humus.

*Secondary treatment* : Treatment of waste-water by biological oxidation after primary treatment by sedimentation.

*Second-stage biochemical oxygen demand* : Part of the biochemical oxygen demand that results from the biological oxidationof nitrogenous materials. Includes the bio-oxidation of ammonia to nitrites and nitrites to nitrates. Oxidation of nitrogenous materials usually does not beginuntil a significant portion of the carbonaceous material has been bio-oxidised in the first stage.

*Sewage* : Sewage is water-carried waste, in solution or suspension, that is intended to be removed from a community. Also known as waste-water.

*Sludge* : Accumulated solids removed from a sedimentation basin, settling tank or clarifier in a water or waste-water treatment plant. Precipitate resulting from the chemical coagulation, flocculation and sedimentation of a water or waste-water.

*Suspended solids* : Solids in suspension in a water or waste-water that can be removed by laboratory filtration techniques, such as membrane filtration.

*Tertiary treatment* : Use of physical, chemical, or biological means to upgrade a secondary effluent.

*Total solids* : The sum of the dissolved and suspended solids in a water or waste-water. Usually expressed in mg/l.

*Transmission* : The movement or transfer of electric energy over an interconnected group of lines and associated equipment between points of supply and points at which it is transformed for delivery to consumers or is delivered to other electric systems. Transmission is considered to end when the energy is transformed for distribution to the consumer.

*Turbine* : A machine for generating rotary mechanical power from the energy of a stream of fluid (such as water, steam or hot gas). Turbines convert the kinetic energy of fluids to mechanical energy through the principles of impulse and reaction or a mixture of the two.

*Turbine generator* : A device that uses steam, heated gases, water flow or wind to cause spinning motion that activates electromagnetic forces and generates electricity.

*Volatile matter* : Matter within a residue that is lost at 600°C ignition temperature. The ignition time must be sufficient to reach a constant weight of residue, usually 15 minutes.

*Vacuum pump* : A vapour pump capable of creating the degree of vacuum necessary to evaporate moisture near room temperature. It extracts noncondensable gases from the condenser by creating a lower pressure at its inlet that exists inside the condenser.

*Waste water* : Spent water that consists of combination of liquid and water-carried wastes from dwellings, business buildings, industrial plants, and institutions, along with any surface or groundwater infiltration. The term has taken precedence over the word sewage.

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