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ENERGY AND ENVIRONMENT—AN ALL TIME SEARCH*†

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Abstract—While worldwide concern for the environment grows, some promising international initiatives take shape. This report gives an outlook of the current problems and summarizes the recent progress. It also outlines a concrete step and some proposals for action. In this context, the study evaluates the potential of hydrogen as a non-polluting fuel and as a true energy carrier for the future. The various other possible approaches are briefly described.

NOMENCLATURE

CFC/s	Chloroflurocarbon/s ($CFCl_2$, $CFCl_3$, etc.)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_x	Carbon oxides (CO and CO_2)
DNA	Deoxyribonucleic acid
H_2	Hydrogen
HC/s	Hydrocarbon/s
H_2O	Water
IR	Infra-red
N_2	Nitrogen
NO	Nitric oxide
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides (NO, N_2O and NO_2)
NO_3^-	Nitrate
PAH	Polynuclear aromatic hydrocarbon
PAN	Peroxyacetyl nitrate
PB_zN	Peroxybenzyl nitrate
Pb	Lead
PbO_x	Lead oxides (PbO, PbO_2, etc.)
ppm	parts per million
O_2	Oxygen
O_3	Ozone
SO_2	Sulphur dioxide
SO_x	Sulphur oxides (SO_2, SO_3, etc.)
SO_4^{2-}	Sulphate
SP	Solid/Suspended particulates
UV	Ultra-violet

*Dedicated to Professor V. Srinivasan on the occasion of his 60th birthday.

†Part of this paper was prepared at the Department of Chemistry, Indian Institute of Technology, Madras 600 036, Tamil Nadu, India.

1. OVERVIEW

Man is recklessly wiping out life on earth: overpopulation, noxious pollution, waste of resources and the destruction of natural habitats. Human activity has caused a marked increase in the concentration of certain environmentally undesired gases in the atmosphere. Most of these gases are given off by burning fossil fuels. This results in two, the most important, global air pollution related problems: the greenhouse effect and thinning of ozone layers. As a consequence, the atmosphere is getting dangerously warmer and could create a climatic calamity. In addition, the influence of different pollutants directly hits human health causing deadly diseases. In other words, the Universe is heading towards a possible disaster.

Ultimately, the world must move away from the use of traditional fuels for most of its energy needs. Otherwise the global warming and the related consequences that result from overreliance on traditional fuels, could produce an increasingly uncertain and potentially bleak future. Even though nuclear energy seems to be promising, it could be used only as a intermediary source by considering various associated problems of public concern. Hence, we ought to get to the source and clean up the smokestacks.

The global awareness towards the growing energy demand, depleting conventional sources and the increasing environmental pollution has resulted in the development of alternative energy sources. Among the available non-fossil options, hydrogen offers the long-term prospect of plentiful supplies of clean energy. The great attraction of hydrogen is essentially a pollution-free combustion—truly a clean and most compatible fuel with the biosphere. The introduction of such a system is inevitable concerning the existing energy and ecology prospects.

2. POPULATION AND ENERGY DEMAND

The demand for energy is growing faster, mainly for the following reasons:

- the continuous increase in world population; today it is about five billion and it is expected to increase further as shown in Fig. 1. During the next century, the population will double, with about 90% of that growth occurring in poorer, developing countries. Expansion is slower in countries like India, China, Brazil and Indonesia, but in those countries the sheer size of existing populations translates into a huge increase in people;
- the growing demands of the developing countries in order to improve their living standards; because of this, the world energy consumption is increasing enormously and is expected to multiply in the coming years. The estimated values for the years 1970 and 1985 respectively are 0.25×10^{17} and 1.07×10^{17} kJ and the projected values for the years 2000 and 2050 respectively are 2.21×10^{17} and 6.30×10^{17} kJ.

If the growth of the world population continues at this rate, it will be virtually impossible to deliver energy equitably at the present consumption levels of the developed nations as well as to satisfy the needs for the developing countries.

Presently, most of the world's energy requirements ($\sim$90%) are met with by fossil fuels, particularly (as per the consumption in the year 1987) oil ($\sim$38%), coal ($\sim$31%) and natural gas ($\sim$20%). At the most, electricity accounts for only about 10% of the energy and is used in technologically advanced prosperous regions. Nuclear power is more controversial; until recently the mere mention of it made environmentalists blanch. They had good reason, considering a couple of the recent major accidents, the problem of radioactive wastes and the horror stories about the United States' weapons plants. The onset of an energy crisis and the deleterious environmental pollution combined with the limited availability of conventional fuels is bringing an end to the fossil fuel era.

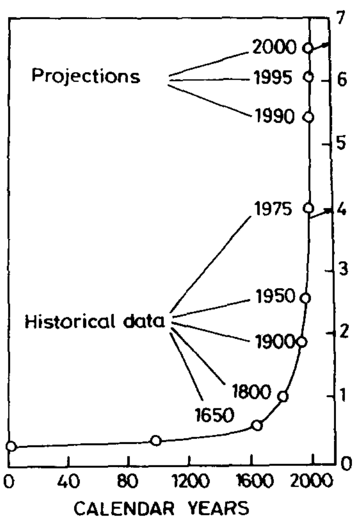

Fig. 1. The world population growth.

The conventional energy sources have not only the desirable characteristics, such as ease of transport and storage, and ready applicability to a broad range of uses, but have proved to be inexpensive to find, produce, transport, refine, consume, and are seemingly capable of never-ending increases in production. As a result, the annual world oil consumption has grown continuously from 150 million barrels in the year 1900 to 22,000 million barrels in the year 1973. In the later years, these figures have increased prodigiously. Because of this redundant consumption, the world oil production is likely to decline by the early decades of the 21st century.

3. CONVENTIONAL FUELS AND THE THREAT

Even today, we are using fossil fuels as an energy source, not because they are the best but because they are readily available and relatively convenient to use. However, besides having end products which are extremely harmful to human health, they have other serious drawbacks. For example:

- the non-renewability of the resources;
- the environmental problem of pollution, and;
- the uneven distribution around the globe.

In short, today's energy is neither abundant nor clean. In other words, it is unacceptable for a problem free life.

3.1. *Health hazards*

Air quality has been deteriorating rapidly over the years resulting in health hazards. The present strategies for reducing air pollution are inefficient and ineffective. The principal pollutants derived from fossil fuel combustion which are the most harmful to health are listed in Table 1. This table also shows the sources and the types of pollutants including the extent of emissions in one particular year. This gives an idea of the contaminants that accumulate in the environment. It has been noticed that all these emissions have been increasing yearly along with the population. The combination of two or more of any of these gases give rise to secondary pollutants (see also Fig. 2), which multiply the health hazards. The effects of the various pollutants on human life are outlined in Table 2. Health consequences from air pollution are expensive and therefore must be financed by society.

CO can kill people in confined spaces (for example, in garages). Some forms of airborne HCs are carcinogenic, while they react with NO_2 and O_2 in the presence of sunlight to form O_3 and smog. O_3 in the stratosphere (upper atmosphere) protects us from UV radiation (I return to this point later) but around us (lower atmosphere or troposphere), it is a health hazard. It is highly reactive and unstable; it can exacerbate breathing problems and inhibit growth in plants. It is expected that for

Table 1. The harmful air pollutants*

Sources	Types-quantity (millions of tons per year)				
	CO	NO_x	SO_x	HC	SP
Transportation (motor vehicles)	75.0	11.5	1.0	13.0	1.5
Stationary fuel (electric power and heating)	0.7	10.0	25.0	2.0	6.6
Industrial process	14.5	0.5	5.0	2.5	10.0
Solid waste disposal and miscellaneous	4.4	0.5	0.4	12.9	1.4
Total	90.6	22.5	31.4	30.4	19.5

* Emissions in the year 1974.

every 1% decrease in atmospheric O_3, there will be a 2% increase in levels of UV radiation. Besides causing sunburn, the rays have been linked to eye disease, such as cataracts, and have weakened immunization systems in humans and other animals. The UV light also carries enough energy to damage DNA and thus disrupt the working of cells, which is why excessive exposure to sunlight is thought to be the primary cause of some skin cancers.

About 320 pollutants have been monitored in the environment, including 60 known to cause cancer. Among the latter are methylene chloride, benzene, formaldehyde, butadiene and carbon tetrachloride. Neurotoxins include xylenes, toluene, methyl ethyl ketone and trichloroethylene. The chemical industry is the largest single source of these toxic pollutants. Toxic wastes and radioactive contaminations could lead to shortages of safe drinking water, the ultimate for human existence.

3.2. *Non-renewability*

The heavy dependence on oil for transportation, heating, power generation and the production of petrochemical feedstock is currently causing a critical situation throughout the world with respect to the ultilization of conventional fuels:

- Severe economic dislocations have been brought about by the high price rather than the lack of supply of crude oil.
- Locating new oil sources is becoming more difficult and the cost of drilling wells is sharply increasing.

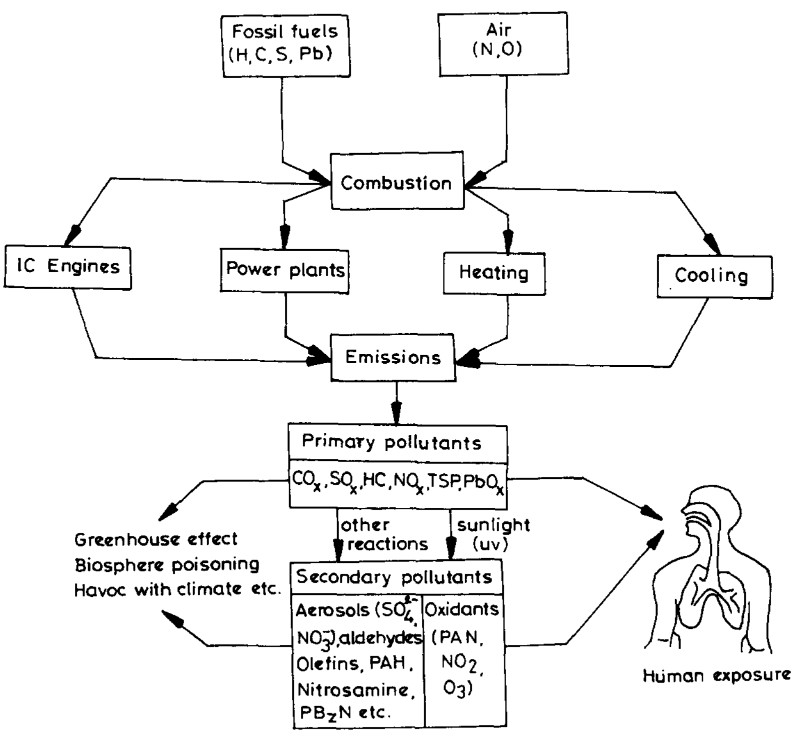

Fig. 2. The generation and the consequences of pollutants from fossil fuels.

Table 2. Pollutants effects on human beings

Types	Causes
Primary pollutants	
CO	Heart disease, strokes, pneumonia, pulmonary tuberculosis, congestion of brain and lungs
SO_x	Acute respiratory infections, chronic pulmonary and cardiac disorders
NO_x	Chronic respiratory infection (chronic bronchitis, emphysema and pulmonary oedema)
HC	Lung and stomach cancer
SP	Destruction of the respiratory epithelium (deleterious effects on the lining in the nose, sinus, throat and lungs), cancer
Pb and PbO_x	Brain damage, cumulative poison (absorbed in red blood cells and bone marrow)
Secondary pollutants	
Oxidants:	
PAN and NO_2	Attacks of acute asthma, allergic respiratory infections, chronic bronchitis and emphysema
O_3	Chest constriction, irritation of mucous membrane, headache, coughing and exhaustion
Aerosols:	
SO_4^{2-} and NO_3^-	Asthma, acute respiratory infections and infant mortality
Others	
Aldehydes, olefins, nitrosamines, PAH, etc.	Respiratory tract carcinoma (carcinogenic—cancer)
Acrolein, PB_zN, etc.	Irritation to the eyes

- As a result, the average selling price of fossil fuels is spiralling.
- Not only is the price of oil increasing steeply, but the sources are also becoming undependable.

Towards the turn of this century or perhaps much earlier, the world demand for crude oil is expected to exceed the production and the consumption of the energy is expected to increase substantially during the next century. Shift from oil to coal could alleviate the problem to some extent, but coal has potentialities as a raw material for the production of a large number of essential chemicals and hence such a shift would not be desirable.

In Fig. 3, the projected production rates of world fossil fuels are shown. The lower line estimates the coal production if it is used as solid fuel. The curve in the middle is the expected rate of production of fluid fuels—petroleum and natural gas. It can be seen that the world fluid fuel production will reach its peak around the year 2010 and then will start to decrease. Curve 1 gives the total fossil fuel production estimates if synthetic gas and gasoline are produced from coal. In this case, production would rise until the year 2030 and would then start to decline.

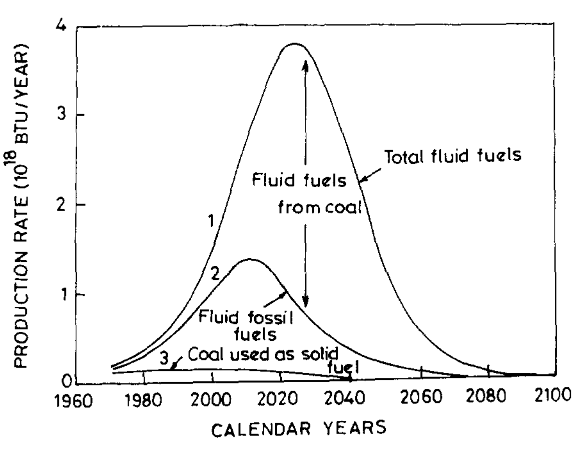

Fig. 3. The projected rate of production of world fossil fuels.

3.3. *Environmental issues*

3.3.1. *Air pollution.* Although the conventional energy sources have all paid to the world's technological progress, they have also contributed to the environmental problems of pollution. An important type of pollution, namely, air pollution is caused mainly by fossil fuels being used to obtain energy for transportation, electricity production, heat generation, etc. (see Fig. 2). Motor vehicles generate more pollution than any other single human activity, even though technologies exist to make exhaust fumes (harmful pollutants) safe. With the enormous increase in the number of fossil fuel driven engines, their emissions have become a major source of atmospheric pollution. As can be seen from Table 1, globally, petrol and diesel engines dump almost half the pollutants into the atmosphere.

A catalytic converter in an automobile reduces some of the pollutants that petrol or diesel engines produce. A modern three-way catalytic converter can eliminate up to 80% of the harmful pollutants. However, researchers have recently found that levels of N_2O rise significantly with this new system too. Studies show that it produces five times as much N_2O as cars without catalytic converters. Thus, the impossibility of keeping the emission from the internal combustion engine clean under all operating conditions of speed and power, or even the use of efficient catalysts means that a fuel change could be the only alternative. Transport vehicles also generate other pollutants, such as airborne Pb, SO_2 (in low quantities), solid particulates and carbon soot. Since diesel has a lot of sulphur, these engines in particular are responsible for high emissions of SO_2.

CO_2 which largely comes from the burning of fossil fuels is one of society's largest waste products. Since the Industrial Revolution, CO_2 in the air has increased enormously. Power stations, internal combustion engines, industries and agriculture all create the problem. Recently, destruction of tropical rain forests has become a major source of CO_2. Worse, the trees are no longer there to take CO_2 from the air. CH_4 is a product of wetland agriculture and fossil fuel extraction. It is also produced from cattle manure and rubbish. Concentrations have doubled over the past 200 years and continues to be a risk. N_2O, given off by N_2 fertilisers and the burning of fossil fuels, is also increasing in the atmosphere. CFCs are synthetic chemicals used in aerosols, foam plastics, and in refrigerators and air conditioners. Studies indicate that the concentration is also increasing rapidly in the environment. Other gases include O_3 in urban smog and halons in fire extinguishers.

3.3.2. *Greenhouse effect*. Gases like CO_2, CH_4, N_2O, O_3, CFCs and other trace gases in the atmosphere act like a greenhouse. They allow the sun's rays to reach the earth, but trap heat which would otherwise radiate back into the space. The visible light from the sun passes through the atmosphere to the earth's surface. As the heat radiation leaves the earth, some of them escapes to space but gases in the atmosphere trap the rest, keeping the earth warm. A build-up of gases, including CO_2, CH_4, N_2O and CFCs prevents additional heat radiation from escaping, thus heating up the earth (by means of trapping IR radiation) excessively. For years, CO_2 levels in the atmosphere have been growing about 1.5 ppm per year. In recent years, it rose twice as much as usual, raising new fears about the global warming due to the CO_2 alone.

Ironically, the same greenhouse effect that may be so dislocating, made earth hospitable to life in the first place. Without a heat-trapping media of naturally occurring CO_2, the planet would have an average surface temperature of only −18°C instead of 15°C. The reason being, CO_2 molecules are transparent to visible light, like the glass panes of a greenhouse, allowing the sun's rays to warm the earth's surface but when the surface gives off its excess heat, it does so not with visible light but with IR radiation. Since CO_2 absorbs IR rays, some of the excess heat stays in the atmosphere rather than escaping into space, thereby raising the mean temperature of the planet. As a result, it would increase the frequency of extreme weather conditions. This could cause the melting of polar ice caps, an increase in mean sea level, shrinking and flooding of coastal areas, and ruining huge tracts of farmland through salinization. These changes are already taking place and are expected to accelerate over the coming years, as the amount of greenhouse gases accumulate in the atmosphere. The amount of heat retained depends on the concentration of these greenhouse gases in the air.

3.3.3. *Ozone layer depletion*. CFCs—these remarkable chemicals are non-toxic and inert, meaning they do not combine easily with other substances. They are perfect as coolants in refrigerators, air conditioners, and propellant gases for spray cans. On the other hand, they destroy O_3 in the stratosphere. Threats to the O_3 layer from emissions of CFCs and from increases of N_2O concentrations, caused by increased application of N_2 fertilizers, agricultural activity and automobile exhausts, have been recognized and assessed. A more immediate concern is that the chlorine released when the CFC molecules break up destroys O_3 molecules. O_3, while being necessary in the stratosphere to serve as a shield against solar UV radiation, is considered undesirable at ground level because of its toxic effects on plants, animals and human beings. The present strategies and the prospects for an alternative are not a pleasant one, but efforts are being focused on making the transition for curbing the greenhouse effect and to save the life-preserving O_3 layer.

3.3.4. *Global warming*. The warming, rapid now, may become even more rapid as a result of the warming itself and it will continue indefinitely unless we take deliberate steps to slow down or stop it. CO_2, is one of the major combustion products of the fossil fuels, the increase of which has been firmly established by reliable measurements. In contrast to both N_2 and O_2, which together make up more than 99% of the atmosphere, CO_2 and several other gases present in smaller amounts have an important role in determining the mean surface temperature of the earth. The accumulation of CO_2 in the atmosphere could drive up the planet's average temperature and there is evidence from space: for example, Mars, which has little CO_2 in its atmosphere, has a surface temperature that reaches −30°C at best, while Venus, with abundant CO_2 has a temperature as high as 450°C.

The observed records reveal a global warming of about 0.5°C from 1860 to 1985 and has been correlated mainly to the increase in CO_2 content, respectively about 290 to 345 ppm. This increase may not appear much, but even the small changes cause a dramatic alterations of the biosphere. It has been predicted that the rise in atmospheric CO_2 from 350 to 700 ppm (projected values from the year 1988 to 2050 respectively) would increase the temperature of the earth's surface by 3–5°C. This would bring greater climatic changes than experienced in the earlier centuries. In recent years, it has been recognized that the atmospheric burden of greenhouse gases other than CO_2, such as CH_4, N_2O, CFCs, are on an increase. As per 1989 estimates the distribution of these gases are: CO_2 (49%), CH_4 (18%), CFCs (14%) and N_2O (6%). In fact, these gases have reached levels at which their combined effect, towards the contribution of global warming, approaches that of CO_2.

Public concern about the greenhouse effect and its potential to warm the earth's atmosphere has so far been focused on CO_2, unleashed into the air as we burn the classical fuels and chop down trees. CH_4 is also a greenhouse gas, second in importance to CO_2. Indeed, molecule for molecule, it traps five to twenty times as much heat as CO_2. Concentrations of CH_4 in the air has been rising at 1% per year, at least since 1950. This is four times the rate of the increase of CO_2. It doubled over these years and within the next 50 years CH_4 could be the prime greenhouse gas. On the other hand, CFC molecules are more powerful as a greenhouse gas than CO_2. For example, when CFCs escape into the atmosphere, some of them are 10,000 to 20,000 times as efficient at trapping heat as is a molecule of CO_2. So CFCs increase the greenhouse effect far out of proportion to their concentration in the air.

3.3.5. *Acid rain.* Sulphuric acid and nitric acid—the main constituents of acid rain—are produced when SO_x and NO_x are converted by the oxidizing agents, such as peroxides and/or O_3, present in the atmosphere. Hydrochloric acid is also produced when chloride, released by the decomposition of CFCs and by other means, is oxidized. Acid rain has already caused widespread acidification of oceans, lakes, rivers, streams, land and forests: it is eroding man-made structures and is partially responsible for arctic haze. Studies indicate that more than one-fifth of Europe's forests are now damaged by acid rain. In particular, Britain's trees are among the most damaged. The other problems with acid rain are:

- it pollutes fresh water, therefore it is difficult for fish and aquatic plants to survive;
- the evidence of direct health threats from acid rain deposition, such as toxic substances in drinking water;
- the widespread economic damage due to the acidic deposits that destroys crops, wreck buildings, and the loss of forests;
- the linkage between acid rain and other problems of pollution, such as global warming.

3.3.6. *Implications.* Thus, the combustion of fossil fuels leads to air pollution, acid rain, and an increase in CO_2 content in the atmosphere resulting in poisoning of the biosphere and deterioration of human health and climate. The increasing CH_4 content is also warming the planet rapidly. By all these adverse effects the earth is warning us of an imminent environmental disaster. The other problems with classical fossil fuel combustion are that the atmosphere and oceans will become hotter. This means that changing weather patterns could make huge areas infertile and uninhabitable. Studies indicate that an increase in atmospheric CO_2 could lead to increased summer dryness of the land surface with potentially serious consequences for agriculture. Storms, powered by increasing ocean temperatures, could cause more devastation. Despite the upsets, conventional fuels are still well established, owing to the lack of an alternative proposition, which is the availability of a primary energy source to entirely satisfy the world's energy demand. As the global temperature begins to increase and patterns of rain fall change, the way plants respond to the new conditions will produce drastic changes to life on earth.

4. NEW APPROACHES AND THE HOPES

4.1. *Nuclear power*

Although nuclear energy does not produce CO_2, it is not the only answer for the existing situation. The increase in the number of nuclear power stations to satisfy a high energy demand will produce more radioactive nuclear waste with no effective means of disposal, besides being prohibitively expensive. Nuclear power, however, turns out to be a great deal more expensive and technically difficult to provide than suggested. When nuclear plants were completed, often far behind schedule, they frequently cost two or three times the figure estimated when they were planned. The performance of many plants has been disappointing with average output well below the capacity initially foreseen. At present, nuclear energy accounts for only about 5% of the total energy demand. Safety problems, the difficulties of disposing of radioactive wastes and mounting public opposition further cloud the picture. Around the world, within a decade or two, nuclear programmes have shrivelled even faster than the market for coal did. The result is that most countries are now once again favouring coal over nuclear power. The accidents reinforce this trend.

4.1.1. *Risks and benefits.* The potentialities of energy supply alternatives indicate that nuclear power must play a significant role in energy production and it appears to be the source with immediate and long term prospects. Nuclear plants have the potential of providing abundant supplies of electricity without spewing pollutants into the atmosphere. However, the costs of making atomic power safe are spiralling out of control. The dangers of radioactivity and nuclear wastes will last for ever. No nuclear reactor is totally safe as long as it produces radioactive waste. Even though increasing amounts of cheaper, safer, nuclear power seem to be attactive, safety comes first in new reactor designs that are demonstrably safer than those in operation. However, a sequence of misfortunes make a direct impact on human life. The accidents both at Three Mile Island (U.S.A.) and Chernobyl (U.S.S.R.) are the best examples to cite. Apart from the psychological problem which makes nuclear power supply unacceptable to many communities, there are some genuine technological, ethical, economical and political problems associated with nuclear power.

4.1.2. *Nuclear induced pollution.* It is widely understood that any major nuclear exchange or explosions would be accompanied by an enormous number of immediate fatalities; nevertheless, a much larger fraction of human population would survive the immediate effects of a nuclear exchange. The well known examples are the two nuclear explosions at Hiroshima and Nagasaki (Japan). A nuclear exchange would insert significant amounts of smoke, fine dust and undesirable chemical species into the atmosphere. The depositions could result in drastic perturbations of the environment. Furthermore, estimations of the amount, distribution, and the subsequent fates of these materials involve large uncertainties. It has been estimated that the smoke emissions from nuclear-initiated fires could produce major atmospheric perturbations.

The production of NO by nuclear explosion, soot and the production of gaseous pollutants by fire ignited by nuclear explosions would pose chemical threats to the atmosphere in the post war period. Among the gaseous emissions from fires are CO, NO_x, and a large number of HCs including many other organic compounds. In the presence of sunlight, these compounds react to form strong oxidants, particularly O_3 and peroxides. In particular, organic peroxides such as PAN and related compounds have strong phototoxic effects.

4.2. *Alternative sources*

The increasing prices of fossil fuels, the deleterious environmental factors associated with coal and nuclear energy, and the finite nature of conventional fuels have forced the world to search for alternative energy sources which should not have the shortcomings that are being experienced at present. The following are some of the desirable characteristics for such a system:

- Abundant availability;
- Renewable nature;
- Environmentally clean;
- High energy content;
- Low cost
- Easily storable;
- Economically transportable;
- Conveniently usable;
- Socially compatible.

There is a wide agreement that the use of traditional fuels must sooner or later be incrementally replaced by non-conventional energy sources. This is one of the most serious challenges that the world as a whole is facing at present. The present status of various sources of energy is schematically represented in Fig. 4. Some of the non-fossil energy sources shown in the figure are renewable in nature, could be adopted for our needs, if proper attention is focused upon it.

Moreover, the non-fossil energy sources are distributed more evenly around the world than the fossil fuels. Every country has one or more of the non-conventional energy sources available. So, each country should be able to produce their own fuel and speed up their development. If bold initiatives in the sphere of energy are not set into motion promptly all over the world, we will be facing most serious consequences. Hence, all of us must turn to renewable energy sources for a perpetually sustainable yield of energy and it is hoped that the renewable energy technologies hold the key for a cleaner and more secure energy future. Therefore, they are one of our bright hopes for energy self-sufficiency and for better energy in the future.

4.2.1. *New opportunities.* The clean energy sources, such as, solar, wind, tidal, wave, oceanthermal, geothermal, hydrogen (H_2), etc. (see also Fig. 4) are almost unlimited in amount and environmentally compatible. However, these options are generally still in the experimental stages. Hence, we should urge an accelaration of demonstration and an implementation of such programmes before the fossil fuel supply is exhausted.

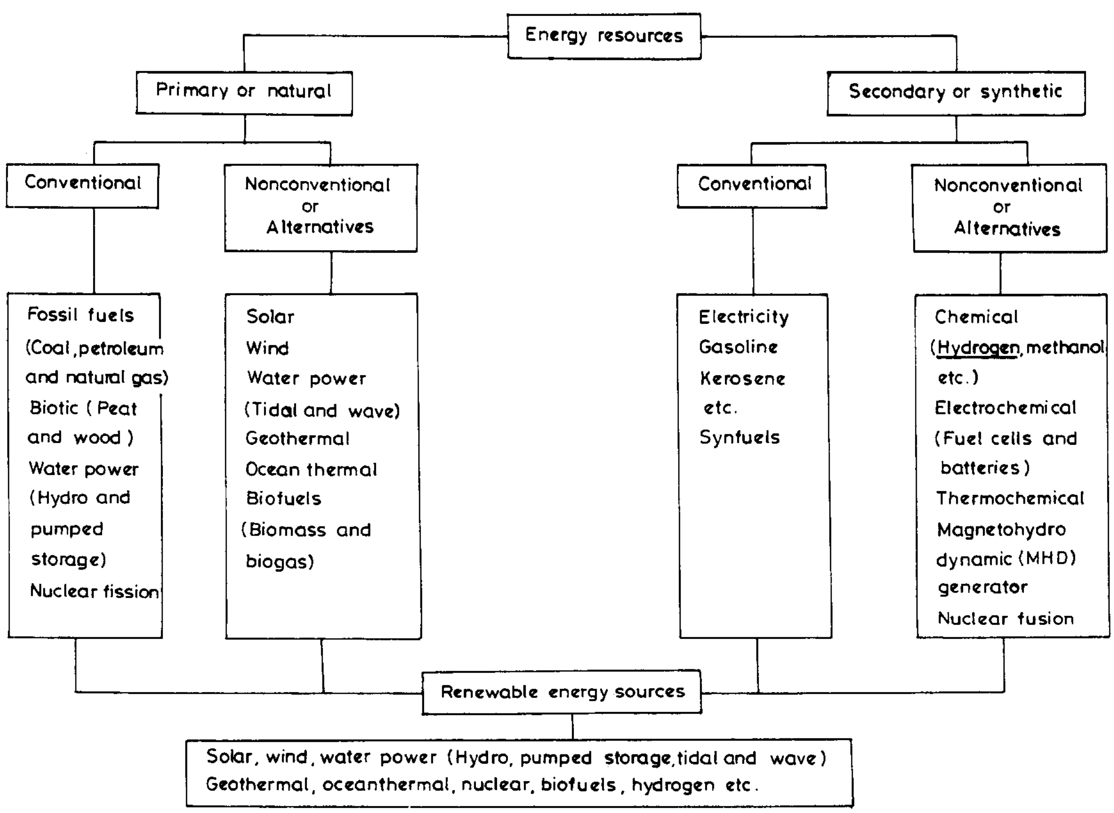

Fig. 4. The global energy resources.

Photovoltaic cells, which by means of solid-state technology turn sunlight into electric current, can make a substantial contribution towards fulfilling the energy needs. However, the drawbacks have been present-day costs and technological immaturity. Advances in the forthcoming years should make it possible for photovoltaics to become one of the world's preferred technologies for generating electrical energy. It will become quite competitive if the production cost drops significantly.

Hydroelectricity and H_2 from direct or indirect solar energy are presently the only conceivable clean energies. Of all the known non-fossil energy sources, only a few are far enough along in their development to be counted on: solar and H_2 (in particular, solar produced H_2), neither of which generates any greenhouse gases at all. They are very attractive, because they produce no waste and they are inexhaustible. It is hoped to see vast tracts of photovoltaic collectors providing cheap electricity that can be transmitted over long distances. Alternatively, the electricity could be used to produce H_2 from H_2O. This could open up all sorts of possibilities.

4.3. *Hydrogen—the clean energy*

The growing concern over the effects of acid rain, high levels of tropospheric O_3, depletion of stratospheric O_3, and the greenhouse effect may provide significant impetus to the greater use of H_2. Direct substitution of H_2 for fuel sources in residential, commercial and industrial sectors will have immediate environmental benefits. First of all, it is important to understand that H_2 itself is not a primary energy source because energy must be supplied in order to produce it. Hence H_2, correctly defined, is an energy (secondary) carrier obtained from H_2O dissociation and burned to steam (H_2O vapour)—a fuel which is totally derived from basic material available anywhere (practically inexhaustible) and of course, a perfectly closed system. All the known systems, such as fossil and nuclear energies, constitute an open system. All the more, these take something somewhere out of the biosphere and return it somewhere else, which creates all sorts of problems for our existence.

H_2 is very abundant; the main constituent element of H_2O; geographically evenly distributed and hence, would be available to both energy-poor and -rich countries. The products of combustion are considered to be non-polluting or at least less polluting (Table 3). Thus, fatal ecological damages caused by classical fuels can be principally excluded. Even though H_2 is a secondary energy carrier, it has emerged as one of the primary options for satisfying the need for environmentally clean energy. In fact, it holds the promise of being a highly efficient energy carrier that can be used in situations where the transfer of energy as electricity is inefficient, impracticable or impossible. It is this potential that has generated such widespread interest in the possibility of a hydrogen economy. However, the sudden drop in crude oil prices of a few years ago was accompanied by a similar precipitous loss of official interest in energy conservation programmes and alternative energy sources, but alarm over global pollution and warming has begun to revive old concerns. Ultimately, in the survival scenario of our planet, clean, non-polluting fuels on a large scale become mandatory very rapidly to replace the unacceptable non-renewable fossil energies towards the twentieth century.

Table 3. Pollutants from the utilization of different energy systems

Sources	CO_x	NO_x	HC	SO_x	HM*	SA†	RA‡
Coal	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Oil	Yes	Yes	Yes	Yes	Yes	No	No
Natural gas	Yes	Yes	No	No	No	No	No
Nuclear	No	No	No	No	No	No	Yes
Hydrogen	No	Yes§	No	No	No	No	No

* Heavy metals; † Soot and ashes; ‡ Radioactivity.

§ In the case of transport vehicles it could be adjusted so that the emission of NO_x is 200 times less than in fossil fuel operated ones.

4.3.1. *Solar hydrogen.* Today, H_2 is made industrially, chiefly by extracting it from natural gas by steam reforming. H_2 can also be produced by electrolysis of H_2O, that is splitting of H_2O molecules into H_2 and O_2. Apart from the various conventional methods of H_2 production based on fossil fuels, modern methods such as coal gasification, water splitting methods which include photolysis, bio-conversion, thermochemical process are being investigated for commercialization. Other methods include electrolysis with an input of electrical energy derived from primary non-conventional energy sources, like solar, wind, geothermal, oceanthermal, etc. At present, H_2 is relatively expensive to produce because of the energy costs involved. If it were produced by using solar and other non-conventional energy sources, the prices would fall. In addition, if H_2 is produced from H_2O using such clean power sources, then it will be a totally non-polluting fuel. On the other hand, the use of fossil fuels to make H_2 would cause a substantial increase in the emission of greenhouse gases. However, the recent reports on the efficiency improvements and the cost reductions in photovoltaic devices can make electrolysis of hydrogen by solar-powered devices cost-effective as other suggested petroleum fuel replacements, such as methanol or ethanol. Hence, H_2 generated by solar electricity, as the environmentally benign transportation fuel of the future.

4.3.2. *Issues and contraints.* H_2 serves as a carrier through which a primary energy source (solar, nuclear, etc.) can be stored, transmitted and ultilized to fulfil present and future energy needs. The resource base is large; it is the cleanest burning of all known fuels and it can be used efficiently, the major combustion product of H_2 being H_2O vapour and hence it is essentially renewable. It produces more energy per unit weight (Table 4). H_2 fuel could be particularly advantageous, since it could be universally employed for household, industrial and automotive applications in a similar manner to the existing petroleum technology. H_2 propulsion opens up the possibility of low-pollutant driving without the need

Table 4. Energy densities of various fuels

Source	Mass specific energy density (10^3 kWh kg^-)
Coal	8.15
Oil	12.10
Natural gas	13.80
Methanol	5.45
Hydrogen	33.50

for a conventional fuel except for the fact that it does also produce little NO_x (see Table 5). It is, however, unavoidable owing to the fact that air constitutes 80% N_2—a problem that can be minimized with better combustion technology. But if the H_2 is made by electrolysing H_2O, using electricity generated by coal or oil, the indirect consequences for the greenhouse effect and for acid rain are as bad as if the vehicle used gasoline.

The major portion of H_2 produced is used as an industrial chemical and a fuel in the petrochemical and chemical process industries—for such uses as petroleum refining, chemical manufacture, production of fertilizers and electronic materials (silicon crystal formation). However, its use as a vehicular fuel attracts greater attention and it is clear that H_2 can be used in every application in which fossil fuels are used. It can be readily converted to mechanical, electrical, or thermal energies with higher efficiencies than that of fossil fuels. Above all, H_2 can easily be substituted for natural gas, diesel and gasoline. So, it complements electricity—the other clean and versatile secondary energy carrier. Typically, H_2 would be transported from the site of production to users as gas through pipelines. Ideally, the current natural gas system would be used for at least the initial stages of a transition.

Unfortunately, despite its unique properties, H_2 has not yet been widely exploited as a fuel. Perhaps the most important factor which limits its use are the difficulties involved in storing it conveniently and economically. The fact that H_2 is a gaseous fuel and has a low density poses a problem for its storage. H_2 has been traditionally stored as liquid in cryogenic containers, or as highly compressed gas in pressure vessels. No matter how good an automotive fuel H_2 may be (see Table 5), it will never find extensive use if it has to be supplied as compressed gas or in liquid form. However, in the last decade there has been a breakthrough after the discovery of metal hydrides—a promising storage media in chemical form. Hence, in recent years attention has been focused on these interesting materials. Other forms of H_2 storage, such as glass microspheres, cryoadsorbents, liquid hydrides, etc. are still in the early stages of development and none are nearly as well developed for vehicular use as metal hydrides.

Table 5. Exhaust gases from different automotive fuels

Source	Emissions ($g\,km^{-1}$)			
	NO_x	CO	HC	CO_2
Gasoline	2.50	15.36	1.82	370.0
Gasoline + H_2	0.52	1.87	2.17	—
Compressed H_2	0.16*	0.15†	0.06†	—
Liquid H_2	0.35*	—	—	—
Hydride H_2	1.40*	0.29†	0.10†	—

* It is anticipated that there would be a significant reduction of NO_x levels by improved combustion characteristics.

† CO and HC emissions are from combustion of excess lubricating oil. This could be kept near zero by periodic inspection and maintenance.

4.3.3. *Automotive fuel.* Technically, H_2 is a good fuel for internal combustion engines, with high efficiency. Automotive vehicles have been converted to H_2 powered operation. Therefore H_2, as a fuel for road transport vehicles, will have a large market in the near future. The main advantages are:

- the exhaust gases consist largely of H_2O vapour. That is, no CO_x or SO_x are emitted, although it inevitably produces some NO_x from reactions with N_2 in the air;
- the existing internal combustion engines can be modified and adopted to H_2 operation;
- the current energy supply network for gas and electricity can be used.

As compared to the conventional propulsion systems, however, H_2 driven engines have a few drawbacks, namely:

- the high weight and large volume of the storage systems, reduce operating range and playload capacity;
- the additional storage and propulsion elements incur higher costs.

Thus, H_2 storage for automobile use is particularly in need of development.

4.3.4. *Superconductivity and cold fusion.* Interestingly, many predictions suggest that when molecular H_2 is made metallic, it will become a superconductor with a very high transition temperature of possibly more than the existing high temperature superconducting oxides (−148°C or 125 K) or even to room temperature. The idea of metallic hydrogen being a high temperature superconductor has attracted much attention. On the other hand, metal hydride systems created excitement, which led to their intense study in the 70s, when superconductivity was found. However, the highest value achieved so far is about −256°C (17 K). One of the reasons for superconductivity is the dense packing of the lattice with hydrogen (H) atoms. Of course, the recent controversial discovery of the cold fusion process is buoying up hydrogen researchers everywhere. Once again, the possible explanation could be the interaction of deuterium (D) atoms, an isotope of hydrogen atom (H), in the metal lattice. If this is true, it will be a breakthrough for a hydrogen energy system.

4.3.5. *Other applications.* Scientific interest in the behaviour of H_2 in metals, alloys and intermetallic compounds has increased rapidly in the recent past largely because of the realization of many energy-related technological applications. For example, in H_2 storage both for mobile and stationary purposes, waste heat storage, thermal storage, cooling systems, heat pumps, fuel cells, H_2 compressors, nuclear fusion and fission reactors, and in the field of catalysis. There are many more small scale applications of metal–H_2 systems in addition to the above mentioned areas. It is the general consensus of scientists that among the energy options available, hydrogen being unique and socially compatible, would start replacing the fossil fuels. The replacement of these classical fuels by H_2 would have another beneficial effect, namely, the remaining fossil fuel resources would be utilized as raw materials for other essential applications. H_2 is, therefore, being considered as an ideal energy carrier. Figure 5 gives a schematic representation of the state of development of hydrogen energy systems in terms of production, transmission, storage and applications.

5. CONCLUDING REMARKS

Impetus for change in the present pattern of energy utilization arises from our inability to sustain a continued increase in power consumption and from mounting concerns about the greenhouse effect, acid rain, O_3 layer thinning or urban pollution. In addition to their environmental and ecological transgressions, fossil fuels have another drawback, namely that distribution is not uniform among the countries of the world. It is important to stress at the outset that the global energy problem does not in anyway involve the absolute shortage of potentially clean energy resources. There are several non-conventional sources available on earth that would supply human need forever, if they could be harnessed. The problem is that these energy resources, as they exist in nature, are not in a form useful for directly meeting immediate human needs. Thus, another aspect of the long-term energy challenge is to find ways to efficiently and inexpensively effect the conversion of this non-conventional energy resources into useful forms.

Never before have the ill effects of fossil fuel burning and of nuclear power been so apparent. The fact that CO_2 and other greenhouse gases in the atmosphere have risen and continue to increase rapidly and the nuclear reactors, which create deadly and long-lasting radioactive waste, have never been so obvious. Thus, the human race is conducting a dangerous experiment on an unprecedented scale. The possible consequences are so scary that we must slow the build-up of CO_2 and other gases through preventive measures, from encouraging energy conservation to developing alternatives to fossil fuels. Although there are still many uncertainties about all these issues, we must act quickly with good judgement at energy planning to save our own lives.

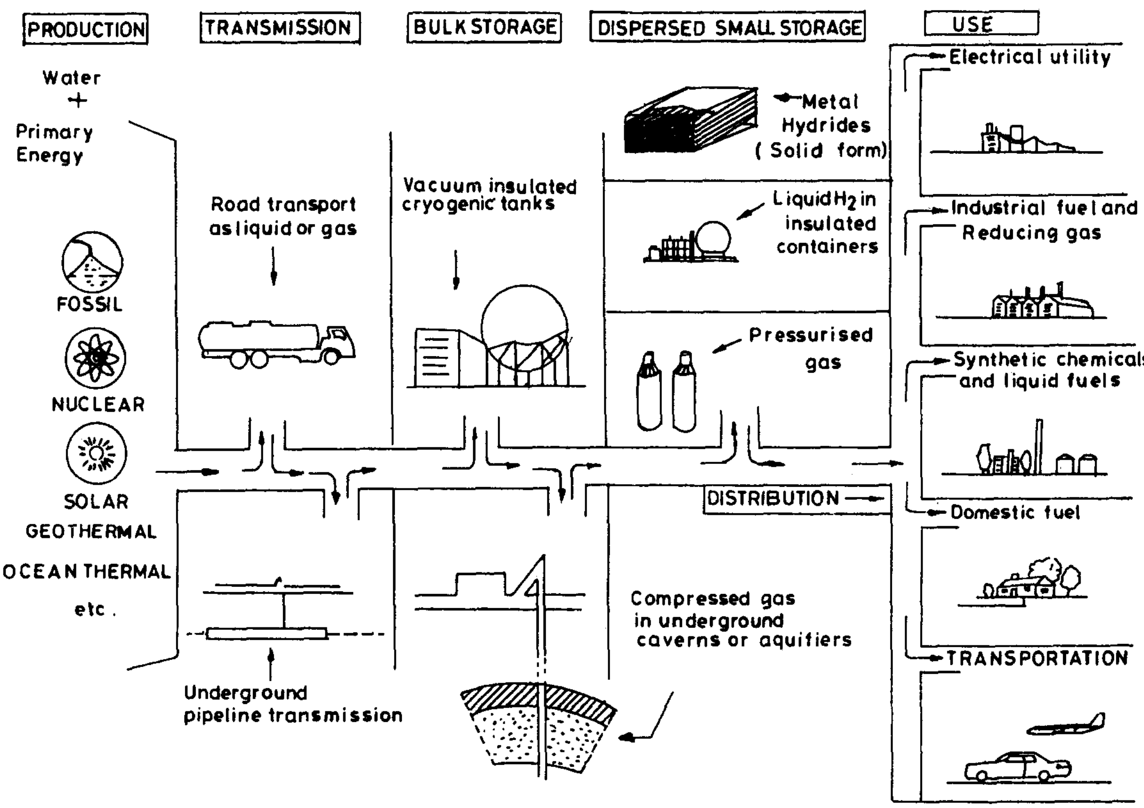

Fig. 5. The hydrogen energy system.

The use of H_2 produced from H_2O using non-fossil electricity, such as from solar energy, could be the most effective way to reduce the emissions of greenhouse gases. H_2 powered vehicles could be socially and environmentally preferred for both surface and air transportation. With a strong research and development effort, and technological progress, H_2 driven vehicles could be cost-competitive within a relatively short period of time. Until a clearly superior energy source emerges research on hydrogen energy related topics must continue. H_2 could play a major role in the problems of energy needs and environmental concern as well as providing mankind with a renewable energy carrier. The hydrogen energy system will be a practical reality within the next few decades and is likely to have an impact similar to that which petroleum fuel had on society at the beginning of this century. Since, however, nothing on this earth is solely advantageous, it seems only fair to mention those areas of a future global solar-hydrogen energy system where scientists, engineers, and technologists should also be careful in order to minimize ecological consequences.

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BIBLIOGRAPHY

R. Siever (with commentaries), *Readings from Scientific American: Energy and Environment*. W.H. Freeman and Company, San Francisco (1979).

A. Stratton, *Energy and Feedstock in the Chemical Industry*. Ellis Horwood, Chichester (1983).

A. L. Hammond, W. D. Metz and T. H. Maugh II, *Energy and the Future*. AAAS, Washington, D.C. (1973).

J. B. Marion, *Energy in Perspective*. Academic Press, New York (1974).

P. Auer (ed.), *Advances in Energy Systems and Technology*, 2 Volumes. Academic Press, New York (1978).

E. L. Harder, *Fundamentals of Energy Production*. John Wiley, New York (1982).

E. Pochin, *Nuclear Radiation: Risks and Benefits*. Clarendon Press, Oxford (1986).

T. N. Veziroğlu (ed.), *Alternative Energy Sources: An International Compendium*, 11 Volumes. Hemisphere, Washington, D.C. (1978).

B. Storensen, *Renewable Energy*. Academic Press, London (1979).

P. R. Pryde, *Non-Conventional Energy Resources*. John Wiley, New York (1983).

T. N. Veziroğlu (ed.), *Hydrogen Energy: Parts A and B*, 2 Volumes. Plenum Press, New York (1975).

T. N. Veziroğlu (ed.), *Hydrogen Energy Progress, Proceedings of the World Hydrogen Energy conferences*. Pergamon Press, New York (1974–1989).

K. E. Cox and K. D. Williamson, *Hydrogen—Its Technology and Implications*, 5 Volumes. CRC Press, Boca Raton, Florida (1979).

L. O. Williams, *Hydrogen Power—An Introduction of Hydrogen Energy and its Applications*. Pergamon Press, Oxford (1980).

P. Hoffmann, *The Forever Fuel—The Story of Hydrogen*. Westview Press, Colorado (1981).

C.-J. Winter and J. Nitsch (eds), *Hydrogen as an Energy Carrier*. Springer, Berlin (1988).

J. O'M. Bockris, *Energy: The Solar-Hydrogen Alternative*. The Architectural Press, London (1976).

T. Ohta (ed.), *Solar-Hydrogen Energy Systems*. Pergamon Press, Oxford (1979).

E. W. Justi, *A Solar-Hydrogen Energy System*. Plenum Press, New York (1987).

J. M. Ogden and R. H. Williams, *Solar Hydrogen—Moving Beyond Fossil Fuels*. World Resources Institute, Washington, D.C. (1989).