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HYDROGEN PATHWAYS FOR MASSIVE SOLAR ENERGY UTILIZATION

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Abstract—Two characteristic features of solar radiation, though beneficial and even essential for plant and animal life, are serious handicaps to the large-scale commercial utilization of solar energy. These are: (1) its diffuse nature and relatively low level of intensity, and (2) its diurnal intermittency and periodic variations. The first-mentioned factor implies a need for large collecting and concentrating devices and vast land areas, which may not always be available, especially in densely populated and industrialized localities, where the energy need will be most. Location of the collectors far removed from the centers of demand will engender the problems of energy transmission. The obvious solution to these problems is to provide an effective means by which sunshine energy can be stored in a form that can be transported and used subsequently when and where required. Conversion to hydrogen through the highly endergonic dissociation of water provides a very capacious and versatile means for solar energy storage and distribution. More importantly, it 'decouples' the primary energy source completely from its end-uses and thus enables it to subserve all the energy needs of industrialized society, unhampered by the constraints characteristic of the prime source and indeed, as efficiently as petroleum fuels. The paper discusses the merits of this proposal and the methods by which it may be achieved in the near term and long term.

INTRODUCTION

The world's oil supply, which became the cause for worldwide concern in 1973–4, received an even more serious set-back in 1979. In that year, the oil-rich countries of the Middle East took a long-term policy decision to cut back severely on their oil production with a view to conserving their oil wealth (their only capital resource) for several decades more. As a result of this decision, oil production by the OPEC group suddenly dropped to levels lower than their 1974 production rate of 27 million barrels per day (mb/d). Indeed, the actuals for the past 3 years were even lower than 27 mb/d. The OPEC output for 1981 was only about 1 billion tons or 20 mb/day. The external availability of OPEC oil is reduced even further by increased domestic utilization on the order of 3 mb/day which may increase even further to 16.7 mb/d. These portentious developments in the global oil trade are reviewed in a recent factual survey by Fesharaki [1].

Oil is an important energy resource accounting for nearly 50% of the world's gross energy production. The impending shortage in its supply will necessitate massive shifts (on the scale of terawatts, TW) to other resource options, which, while drastically reducing dependence on natural petroleum, will provide the required mix of electricity, heat and motor fuel.

According to detailed systems analysis of global energy perspectives completed recently at the IIASA [2, 3], the requirement of motor fuels for gound air transportation will on the average, constitute roughly one-fifth of the total secondary supplied, even after allowing for substantial economies in fuel consumption. In quantitative terms, it is estimated that the requirement of carry-on-board fuels for transport systems will rise to 100–160 mb/d of oil-equivalent or 7–11 TW by the year 2030. For comparison, the total energy consumption of the world is around 9 TW (excluding the consumption of non-commercial energy sources in less-developed region) at the present time and is expected to increase 3- to 5-fold over the next five decades.

These figures illustrate the quantitative and qualitative aspects of the technological challenge involved in the task of replacing natural petroleum by other energy sources and provide the relevant background to the discussion of the alternative energy sources listed in Table 1, along with their respective potentials, limitations and constraints.

The coal reserves of the world as a whole are no doubt very large, but the bulk of the economically recoverable reserves (over 90%) are held in just three geopolitical regions: U.S.A., U.S.S.R. and Eastern Europe and mainland China. Large parts of the world (e.g. South America and Africa) possess relatively insignificant amounts of coal. A massive expansion of coal utilization in sufficient measure to compensate for deficiencies in oil supplies will call for a tremendous enlargement of the entire chain of operations from mining through transport to combustion or conversion, involving long lead times and hugh capital investments of unprecedented dimensions. The health hazards and environmental damage associated with each of these operations and particularly the dangers of large increases in atmospheric CO_2 are only too well known. Finally, coal is also a finite resource and at a modest 4% growth the present stocks may not last more than 70 years [5]. It would not be wise, therefore, to base a long-term energy supply strategy on a resource of

Table 1. Estimated potentials of alternative energy sources (excluding oil)

Resource	World reserve TW(th) yr	Production rate TW(th) yr/yr	Reference	Limitations and constraints to attain stated production rate
Coal	1,700 (recoverable)	10	[4]	Engineering environment and mining hazards. CO_2 build-up. Resource depletion. Competing metallurgical demands
Nuclear (LWR)	300	<10	[4]	Engineering, Resource depletion
Nuclear (FBR)	300 000	17	[4]	Engineering. Radiation hazards. Safety risks. Societal opposition
Geothermal	<1	<0.5	[4]	Resource limitation. Pollution. Transmission
Hydro-kinetic (falling water, tides, waves)	6/yr	3–5	[4, 5]	Engineering, Reliability. Transmission losses. Inter-regional political issues
Wind	20/yr	3	[6]	Wind speeds. Geographical and seasonal variations. Intermittance. Engineering
OTEC	100/yr	1–10	[7]	Engineering. Materials. Transmission. Economics. Climatic effects
Biomass	Variable	3–7.5	[5, 8]	Land availability. Agro-inputs. Competing demands for produce
Biogas	Variable	2.5	[9]	Resource limitation
Solar radiation	33 000/yr	3–50	[4, 10]	Materials. Technology. Build-up rates. Land area. Transmission, Economics. Diurnal and seasonal variation

limited life. It can at best provide interim relief for the next 20–30 years.

The uranium resources of the earth are also limited (20 million tons) and are not sufficient to last beyond another 50 years at the estimated growth rates, unless reprocessing with fast breeder technology is adopted. Risks associated with unregulated reprocessing are so grave and real and public opposition is so formidable that eventually the advocation for FBR may have to be given up.

SPECULATIONS ON SOLAR ENERGY RESOURCE

The immense magnitude of solar radiant energy has attracted worldwide speculation on utilizing it as a major energy resource alternative to fossil and nuclear fuels, if not immediately, at least a few decades hence, when terrestrial energy sources will be found severly inadequate to meet the energy demands of the future. But some of the natural characteristics of sunshine such as its diurnal intermittance, large seasonal variations and low flux density have limited its applications to low-level thermal application and small-scale power generation in special situations. Unless solar energy can be transformed economically into fuel materials of high thermal quality, which can be stored, traded and transported in bulk over land and sea, there appears to be little chance of its rising to the status of a major commercial energy source. Conversion to chemical fuels will provide complete decoupling of the solar resource from its usage and thus confer unlimited versatility on its application.

CONVERSION OPTIONS

There are basically two practical options for the conversion of solar irradiance into useful fuels. One is the natural photosynthetic route of biofarming or energy plantation, followed by conversion of the primary plant produce into alcohols and hydrocarbons. The other option aims at the production of hydrogen either directly (by biophotolysis, photoelectrolysis or thermochemical splitting of water) or indirectly through the intermediate conversion to electricity followed by electrolysis.

The first-mentioned option (the 'soft' option) has the virtue of being ecologically benign and immediately applicable on a large scale with present human and material resources without heavy demand on capital investment. But the net efficiency of photoconversion is so low (about 1% generally) that the average energy worth of the the harvested produce works out to under 1 W(e) per m^2 [8]. This suffers further reduction if the plantation energy inputs are taken into account. According to the same source [8], the sustainable perennial energy yield from silviculture is indeed much less about 0.14 W(th)/m^2 and the yield of alcohol from sugarcane cultivation is worth only about 0.3 W(th) per m^2 without deducting the energy inputs required for cultivation and alcohol production. These figures quoted from a biomass-biased paper show that the dedicated deployment of cultivable land area solely for energy plantation is not a fruitful proposition, if we reckon the net energy yield per acre, ignoring other considerations.

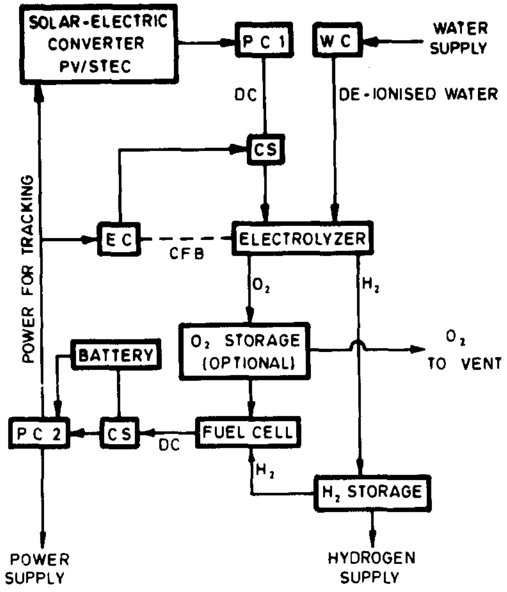
The other option, namely, conversion to hydrogen, has many advantages deriving from the commercial status of hydrogen both as a chemical feedstock and as a versatile fuel which can substitute for petrofuels in virtually all of the latters' applications. Hydrogen has a very special two-way relationship with electricity. The process of electrolysis by which hydrogen is produced from water can be reversed in a fuel-cell to regenerate electricity at high efficiency. Hydrogen can therefore serve as a medium for storage and transmission of electricity in power generation systems. The future commercial prospects of hydrogen in both energy and non-energy markets have been reviewed recently by van Deelen [11] and by Hanson *et al.* [12]. The latter reference, reviews the market economics of hydrogen production with solar energy resources.

SOLAR-HYDROGEN CONVERSION TECHNIQUES

The biophotolytic, photoelectrolytic, photocatalytic, thermochemical and such other techniques for the direct decomposition of water are still being researched at the basic level. They have therefore been excluded from the purview of this paper. On the other hand, both halves of the solar–electrical–hydrogen route have matured into commercially viable technologies. These will be considered in separate parts.

CONVERSION OF SOLAR ENERGY INTO ELECTRICITY

Solar radiant energy can be transmuted into electricity through the techniques solar–thermal–electric conversion (STEC) and solar–photovoltaic (SPV). Both these techniques have been developed competitively to the stage of demonstrative experimentation on the scale of MW. The technique of OTEC, which is aimed at exploiting the temperature gradients in the oceans for power generation, has still a long way to catch up with a state of development of STEC and SPV in terms of system engineering, scale of experimentation and fabrication. Although the thermal resource of the oceans is indeed almost infinite, the rather low-temperature differential ($\Delta T = 18$–22 K) available at most of the prospective ocean sites limits the net efficiency of conversion to barely 2–3% and this necessitates huge quantities of sea-water to be circulated through the OTEC plant. This feature, coupled with considerations of economy of scale which suggest a minimum unit capacity of 250 MWe, translates into unusually huge dimensions of nearly every part of an OTEC plant. Apart from this unsolved major problem of fabrication engineering, there are numerous others affecting the longevity and maintenance of the OTEC plant in mid-ocean sites, the implications of which are yet to be assessed. The focus of this paper is, therefore, on STEC and SPV as the most likely winners in the game of large (multi-MW) scale conversion of solar energy. A block diagram showing the bare essentials of a simple solar–electric–hydrogen installation is shown in Fig. 1. The principal elements of the system are the solar–electric converter



P C = Power-conditioner
W C = Water-conditioner
E C = Electrolyzer-control (MPPT)
C S = Control switch
C F B = Control feed-back
D C = Direct current

Fig. 1. Solar–electric–hydrogen system (schematic).

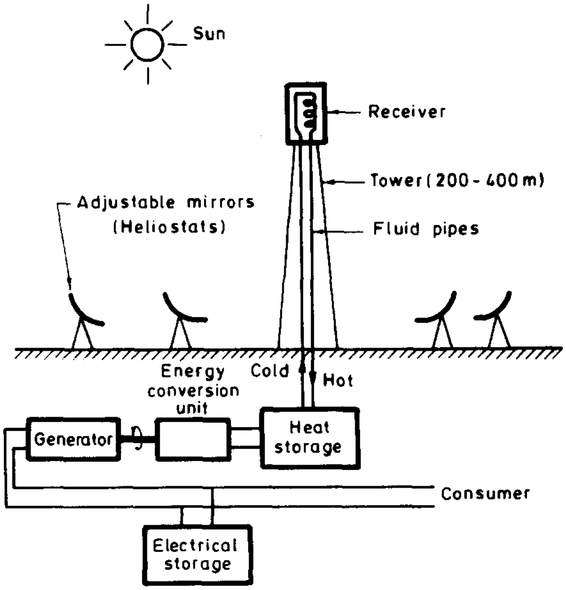


Fig. 2. A large capacity solar–thermal–electric conversion system (STEC).

(STEC or PV) and water electrolyzer. A fuel-cell is added to provide indigenous on-site power supply on demand and a battery will be useful as 'buffering' against fluctuations. Detailed descriptions of STEC and PV systems are available in the many specialized texts and reviews that have appeared in recent years.

The solar–thermal–electric conversion (STEC) operates on the same engineering principle as a normal thermal power-plant (vapor-driven turbogenerator) except that solar heat substitutes for fossil or nuclear fuels as the thermal resource. The basic elements of a typical STEC plant are the optical collector/reflector system (heat source), the receiver, various heat exchangers like boiler, the prime mover/ electric generator and a thermal storage unit. Figure 2 is a highly schematic representation of a STEC installation. The central receiver system consists of concentric arrays of two-axis tracking mirrors (heliostats) which redirect and focus the solar radiation on to an absorber (located at the top of a central tower) to heat up and vaporize the working fluid (typically water) of the turbo-generator. All the components of the STEC plant (including the heliostats) can be mass-produced with technology available today. The other important advantages of STEC are that it utilizes the entire range of the solar spectrum and achieves a reasonably high conversion efficiency (> 20% of the incident solar radiation). The provision for thermal storage will facilitate operation of the plant outside the sunshine hours, i.e. for 12–18 h or even longer per day depending on the size and nature of the storage medium. Considerations of economy of scale (based largely on the operational economy of the turbogenerator which is the major unit) require a minimum generating capacity of 100 MW(e) per unit plant. This would require a heliostat system of about 20000 tracking mirrors (each 40 m^2 area) spreading an area of 3–4 km^2. Plant costs (1975 US \$) projected for 1985 are in the range of \$12000/KWe which may slide down to \$2000/KWe by the turn of the century.

Compared to STEC, photovoltaic generators are relatively simple, as DC electricity is produced directly when light falls on flat plates of solar cells (basically, *p–n* semiconductor junctions), thereby obviating the need for thermo-mechanical intermediaries and other complexities of STEC plants. This greatly simplifies plant maintenance, Silicon-based solar cells have been successfully employed as on-board power sources in space research and are now commercially available for terrestrial applications. Though their photo-response is limited to only a small portion of the solar spectrum (400–1100 nm). Conversion efficiencies exceeding 15% overall are attainable with crystalline silicon cells. For large-scale power generation, solar cells offer the important advantage of modular sub-assemblies or 'building blocks' with which the plant can be erected and commissioned in stages and power can be derived right from the start of the erection program. Another advantage of modular build-up is that technical innovations such as improved types of solar cells and economic benefits of research can be incorporated at each stage of expansion. The major obstacles in the way of large-scale use of solar PV conversion are (1) their high cost — presently around \$7 per peak W and (2) their not being produced in the quantities required. Extensive research programs are now under way to extend modern mass-production techniques to make low-cost solar arrays available by 1985. Even if these targets are attained, the fact that solar cells can operate only in daylight (which unlike heat, cannot be stored) will be an unavoidable liability factor which will reduce the effective annual operating time of solar cells to less than 3000 h even in regions of high insolation. The specific power output of 'state-of-the-art' commercial solar cells being of the order of 60 W/m^2 module area under 'standard operating conditions' the total annual energy output will be less than 180 kWh/m^2 of module area with fixed tilted arrays and about 30% more with two-axis tracking. These figures translate into total module area requirements of 3.5–5.5 km^2 per 100 MWe, which, incidentally, is comparable with area requirement of the collector system of STEC plants. This range corresponds to an electrical power yield of 20–30 W/m^2 which is more than 100 times the areal specific power yield from dedicated energy plantations.

ELECTROLYSIS OF WATER

Water electrolysis is a well established industrial process for the production of hydrogen and a detailed overview of the process and its economics is available [13].

Three types of advanced technologies are under vigorous development for improvement of performance and reduction of plant cost. There are the unipolar alkaline the bipolar alkaline and the solid polymer electrolyte (SPE) types. It is widely expected that as a result of these efforts, advanced types of high capacity water electrolyzers with voltage efficiencies of 90–95% will be commercially available during 1965–1990 in the cost range of \$100–150 per kW(e) (1977 US \$). The point sought to be brought out here is that the cost of the electrolyzer will be less than 10% of the cost of the STEC or PV solar–electric converter, but the advantages accruing therefrom far outweigh this small additional investment.

SUMMARY AND CONCLUSIONS

In the decades to come, energy production from the world's fossil and nuclear resources will become more and more restricted due to various limiting constraints and attention will be directed increasingly to renewable energy sources. The maximum production potentials attainable with these are listed in Table 1. Terrestrial resources, such as hydro-power, biomass and windpower, even if they are vigorously exploited, can meet only a fraction of the growing global energy needs, which may pass the 50 TW(th) mark by the middle of the next century. In such a situation, the world will have to turn to the inexhaustible income of solar irra-

Table 2. Global distribution of desert areas with high insolation

Desert/region	Nominal area of desert (10^6 km^2)	Nominal annual thermal energy flux (kW-h(th)/m^2)
North Africa	7.77	2300
Arabian Peninsula	1.30	2500
Australia	1.55	2000
Kalahari	0.52	2000
Thar (India)	0.26	2000
California	0.35	2200
Mexico	0.15	2200
Total/average	11.90	2190 (ave)

diance for massive energy supplies. In this context, the direct conversion of sunshine energy into electrical power has enormous scope for application in the future.

Direct conversion can be effected either through heat-driven turbogenerators (STEC) or through photovoltaic solar arrays. Though both these techniques show positive promise of large-scale applicability, the rather low specific energy yields of 500–700 W-h per m^2 per day may pose siting problems through large land area requirements (3.5–5.5 km^2 per 100 MW-e) because of competitive pressures from other needs and uses for land. The problem will be felt particularly severely when seeking sites for central power stations of gigawatt capacities. Fortunately according to a survey quoted by Kreith and Kreider [14] about 12 million km^2 of sunny desert lands are available in different parts of the globe (Table 2).

Incidentally these deserts are distributed within the Tropics of Cancer and Capricorn (latitude ± 20°). Endowed with abundant sunshine throughout the year, these areas offer attractive prospects for the location of solar energy conversion plants. The insolation on just 10% of these lands at 25% conversion efficiency (achievable by STEC) can yield roughly 75 TW yr/yr. By the same token, 10% of the California desert will provide 2 million GW h (e)/yr which was equivalent to the yield of nearly 400–1000-MW(u) thermal plants operating at 60% design capacity.

The main snag in this concept of desert solar energy conversion (DESEC) is that, with the exception of a few small deserts like those in California (the electric output from which can be fed directly into the national grid), the major deserts of the world are distant and separated by sea from the regions of intense energy consumption. This will render it difficult, if not impossible, to transmit the desert produced power to the regions needing it. This difficulty can be successfully overcome by converting the electrical energy produced into hydrogen via electrolysis. The hydrogen thus produced can either be transmitted as gas through pipes or liquefied or converted to liquid ammonia and shipped overseas as LH_2 or LNH_3 in special tankers. Conversion to hydrogen will virtually transform the abundant solar energy of the deserts into an exportable merchandise which (unlike petroleum) will never deplete. The electrolysis plant (and the associated hydrogen storage and fuel-cell facilities) may be located either along with the STEC/PV system in the desert site or at the port of export according to the dictates of convenience and cost considerations. The total system will comprise the elements shown in Fig. 1.

Water will be needed in substantial quantities (1) as working fluid and utility in the STEC option, (2) for cooling the solar cell modules in the PV option, and (3) as chemical feedstock and utility in the water electrolysis and fuel-cell plants. Fortunately almost all the desert areas are fringed by seas. Some are, in addition, within accessible range of big rivers. The water from these resources will have to be suitably processed (desalinated) to make it acceptable in STEC/PV plants and should be further deionized for use in SPE electrolysis.

The isolated nature, hostile climatic conditions and uninhabitability of desert areas will necessitate providing the solar–electric conversion system with automatic control devices (robots) so that it may be operated with the minimum of personnel and maintenance. Perhaps, in this regard, PV systems may be more suitable, if their costs can be brought down and their service lifetimes established to be competitive with STEC. The enormous amount of research that is now being invested in the development of PV-power plants raises hopes of such a situation materializing with the next 20 years.

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