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Hydrogen and the Alternative Energy Options

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COMPONENTS OF THE ENERGY PROBLEM

The past few years have witnessed a big upsurge of concern about energy. The so-called 'energy problem' has been the subject of numerous conferences of all kinds of specialists—— not only engineers, but also scientists, economists, sociologists and policy makers. Apparently, what has triggered all this new concern and activity about energy, is the sudden realization that petroleum resources which now provide the major share of the global energy needs, are depleting rapidly and may, it is feared, become very scarce and expensive even before the end of this century (see Fig. 1). At the same time, to make matters worse, the world's requirement of energy, which is very big already, threatens to grow even bigger in the future. So, this energy problem arises mainly out of the growing mismatch between supply and demand in the energy market and the ponderousness of the gap to be bridged. It would be instructive to have an idea of the magnitude of the problem in quantitative terms.

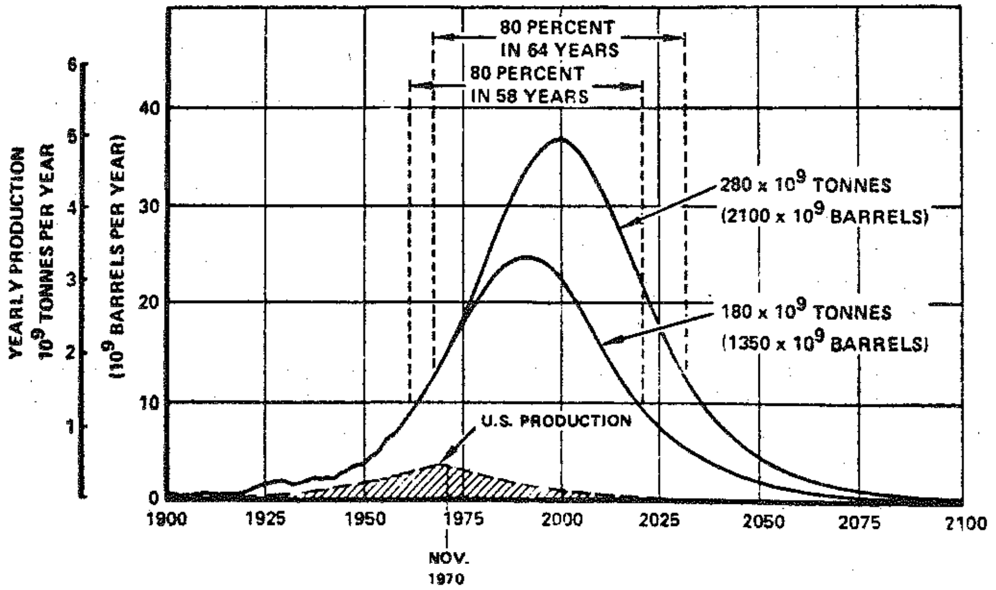

Fig. 1 Two estimates of worldwide production of crude oil. [1]

The total world energy consumption today is close to 8 TW years/year. (TW = 10^{12}W. 1 TW year = 1 billion (10^9) tons of coal equivalent/year = 14 (10^6) barrels of oil/day). Against this, 3.5 TW years/year are provided by oil, nearly half of which comes from the Persian Gulf region alone.

The world has today an estimated population of 4 billion people and so, the average per capita consumption of energy is about 2 kW years/year or 2 kW for short. This average comes from widespread contributions. It is close to 11 kW in the USA, 5-6 in Western Europe, about 4 in Japan, while in most of the developing countries (including India) it is abominably low—roughly 0.2 kW of commercial energy (oil, coal, electricity) plus 0.2 to 0.3 kW of non-commercial energy (fire-wood, dung, animal power etc.)

Inevitably, the world population will continue to grow and it is estimated that it will be 8 billion by the year 2030, to put it at a rather conservative estimate. At the same time, one should also expect a substantial improvement in living standards and GNP in the developing regions of the world and with that a substantial increase in the per capita energy consumption. Allowing for a possible decrease in the per capita values in the affluent countries (largely due to improvements in efficiency of energy usage and conservation measures), it would be reasonable to expect the world average per capita consumption to increase to *at least* 3 kW, though 5 kW per capita would be a more satisfying figure. This means that in another 50 years from now the world energy bill will be between 24 and 40 TW years/year—i.e. 3 to 5 times the current demand—which is a huge lot of energy to reckon with. One more energy figure can be given to illustrate the point. The integrated consumption between now and 2030 A.D. will be around 1000 to 1400 TW years and will, of course, continue to grow. If one tries to match this figure with the known and prophesied reserves of conventional energy resources (such as oil and coal) the outcome will be truly alarming.

The resultant of growing demand and depleting reserves is a peaking of total production of fossil fuels (i.e. oil + coal) around 2030-2050, after which the supplies of these essential energy source will dwindle rapidly (Fig. 2). The situation does not allow of any complacency, because 50 years is not a very long period in the context of national, regional or global development programmes.

The future prospects are particularly serious for the developing countries where the populations are large and the per capita energy has to increase 10 to 15 times the present value in order to secure a reasonable standard of living for these people. The result will be a very big increase in the total energy requirements of these countries. And, we shall have to do without oil, which has so far been the mainstay of the world's energy needs, and on greatly reduced supply of coal.

ALTERNATIVE ENERGY SOURCES

A number of alternative (non-fossil) energy sources are being considered for meeting the big energy need of the future. These include nuclear, solar, hydro-electric, ocean thermal and geothermal energy. To make up for the oil shortages in the near term (i.e. over the next 15 to 20 years), a big expansion of coal based energy has also been recommended.

The alternative energy sources mentioned above can yield, primarily, thermal energy, mechanical energy, electrical energy or chemical energy, the major direct product being, of course, thermal energy. All these alternatives suffer by comparison with oil in one important

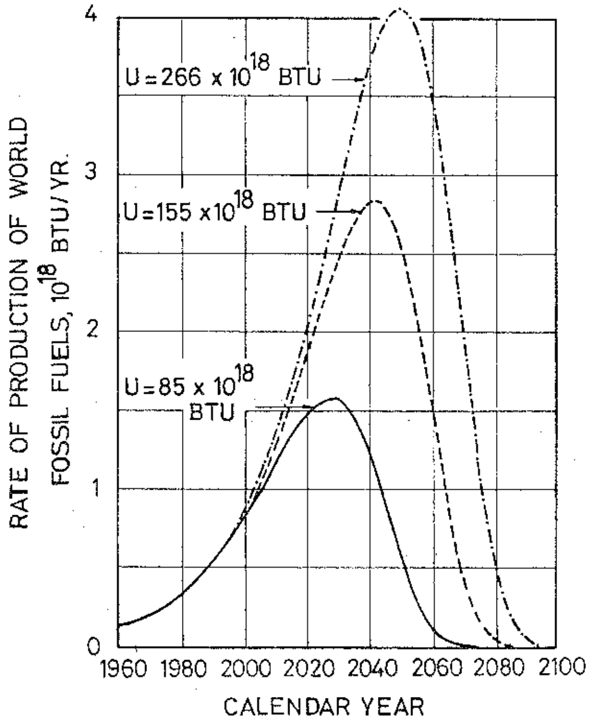

Fig. 2 Depletion of world fossil fuel resources. ('U' denotes ultimate resource). [2]

respect, namely, the flexibility of usage of the energy source. Whereas oil is portable and can be transported to the spot where the energy is required and used there (e.g. in automobiles, air-planes, captive power generators), this mobility is not available with the other sources. Even with coal, portability is severely restricted. Unlike oil which is both an energy source and an energy-carrier, the other energy sources are site-specific i.e. located at a particular place, and the energy produced by them has to be transmitted to the place of requirement after conversion into a form suitable for transmission and utilisation. The current practice that is followed almost invariably is to convert the primary thermal or mechanical energy into electricity, in which form it is transmitted to the user-centres.

LIMITATIONS OF ELECTRICITY

Electricity is no doubt a clean and convenient form of energy and serves certain unique purposes best—such as lighting and a variety of domestic, industrial and transportation power applications with which we are all familiar. But there are techno-economic limitations to the use of electricity, which we shall presently review.

The major share of electricity generation is derived by conversion of primary thermal energy via mechanical energy. Because of thermodynamic limitations set by the Carnot theorem, the overall efficiency of conversion of heat into electrical power seldom exceeds 35 per cent. It is difficult to foresee any major break-through in power-generation technology which would improve on this efficiency significantly. Experts say that any increase beyond

40 per cent is highly improbable. Furthermore, the generation of electrical energy is highly capital intensive. At the present time, the average capital costs amount to roughly $ 1000 per kWe for production and another $ 1000/kWe for transmission and distribution. Those capital costs become larger as the share of electricity of the total is increased. Increase of power generation capacity will entail a corresponding increase in the transmission-line and grid capacity, as the existing grid capacity will in most cases be inadequate. One has to consider in this connection, whether the existing conjestion of overhead high tension lines will allow of further expansion. In many countries, e.g. the USA, there is growing opposition on environmental grounds against the growth of overhead 'wire-scapes', as the bizarre criss-cross of high tension cables is called. The alternative of underground cabling will be very expensive. The transmission of electricity is subject to ohmic losses which add materially to the cost of power delivered to the consumer.

A further difficulty with electricity is that it cannot be stored as such on a large scale. During off-peak periods, when the power off-take is much lower than the normal capacity of the plant, the excess power available calls for storage. The usual mode of storage is to utilise the idle power to pump up water to an elevated tank, from where the water can flow down through turbines to regenerate power when required. This requires a lot of land area which it may not be always possible to find or provide. Where storage is not possible, the output has to be adjusted to match the load. This cannot be achieved accurately, with the result that a lot of power will be wasted. The importance of load levelling and off-peak storage of power will be felt even more keenly with the new generation of super thermal power stations which have rated capacities of several thousand megawatts.

For a variety of reasons, electricity accounts for no more than 20 per cent of the total energy used, the remaining 80 per cent being mostly in the form of fluid fuels—gas and oil. For some applications—e.g. aviation—it is impossible to switch to electricity, while in others the use of electricity will require massive changes in the types of appliances and this would not be economically feasible even in very affluent countries. Moreover, electricity is an expensive form of energy—expensive to produce and expensive to transmit and distribute—and economic considerations will weigh heavily against increasing the proportion of electricity in the energy usage pattern of any country beyond 30 per cent, at the most. So, a rational perspective planning of energy development for the next 50 years would aim at a mixed energy base, the composition of which would be 20-30 per cent electrical and 70-80 per cent non-electrical combustible fluid fuel. In terms of the total energy requirement of 24 to 40 TW years/year in 2030 AD, this would mean achieving a production capacity of 20 to 30 TW years/year equivalent of combustible fuel, with scope for further growth of fuel production. Now the all-important question is: *What is the fluid fuel that would adequately meet the need*?

CRITERIA FOR A SECONDARY FUEL

Ideally, a secondary fuel should have a total use cycle which is *economic*, *energy-efficient*, *safe and environmentally sound.* If it is not economic, relative to competing fuels or energy forms, the other criteria become academic. In addition to these four general criteria, there are more specific criteria for the three phases of the use cycle—namely, production of the secondary fuel, its transport and storage, and its final end use—that an ideal secondary fuel should satisfy.

Production: The secondary fuel should be derived from a resource that is abundant and renewable. Its means of production should be sufficiently flexible so that it can use energy from a variety of primary sources. In short, the secondary fuel should not be based on scarce, limited or depletable material or energy resources.

Transport and storage: Although it might be desirable to produce the secondary fuel when and where it is to be used, this is not feasible for large-scale, highly distributed usage. Therefore, the secondary fuel should be readily transportable and storable. Storage decouples production from end use, thereby allowing for the production of the secondary fuel during the off-peak hours in the direct demand for the output of a primary power station.

End use: The secondary fuel should be applicable to a wide range of end uses throughout the residential, commercial, industrial and transportation sectors.

ALTERNATIVE SYNTHETIC FUELS

The alternative secondary fuels that have been suggested either as a replacement for petroleum or as a running-mate to electricity are: synthetic liquid hydrocarbons, methane, methanol, ethanol, hydrazine, ammonia, and hydrogen.

Some general comments about these alternative candidate fuels follow:

a) Synthetic hydrocarbons are synthetic equivalents of natural petroleum and were created in the 1930's by Germany as a war time necessity. Produced from coal, via gasification (i.e. production of water gas, $CO + H_2$), it has proved to be very expensive.

b) Methane (CH_4) is a synthetic substitute for natural gas, supplies of which are rapidly dwindling. Usually produced from coal through water gas, it is also contained in biogas produced by bacterial fermentation of animal dung and sewage matter.

c) Methanol (CH_4O) is an important industrial chemical and solvent, usually produced from coal through water gas by a high pressure synthesis process. It is highly poisonous.

d) Ethanol (C_2H_6O) is common alcohol, produced by fermentation of sugar. In recent years, biochemical processes have been developed for producing it in large quantities from cellulose wastes.

e) Ammonia (NH_3) is the basic ingredient of chemical fertilizers and is routinely produced on a very large scale for this purpose from nitrogen and hydrogen by a high pressure synthesis process.

f) Hydrazine (N_2H_4) is produced from ammonia. Its main advantage over ammonia is that it is a liquid (boiling point = 131.5°C). Ammonia is a gas at ordinary temperature. Both these materials have been suggested and demonstrated as internal combustion engine fuels in place of petroleum, on account of their non-polluting combustion characteristics, but the proposal has remained sterile because of their high cost of production. The high pressure synthesis of ammonia is a highly energy intensive process. Per unit weight of ammonia, it consumes a lot more energy than can be derived by its combustion. Hydrazine is unstable and dissociates in contact with metals into ammonia, nitrogen and hydrogen.

The alternative chemical fuels which are under active consideration are synthetic liquid hydrocarbons, methane, methanol, ethanol and hydrogen. Of these, the first one is very expensive on plant cost and coal requirement. Its only advantage lies in its offering continuity of the existing petro-fuel distribution system, but this will be only a temporary and limited advantage. It is open to the same objections as natural petroleum with regard to environmental pollution. The production of methane and methanol is also subject to limitations of long-range availability of coal—which is a depletable resource. The production of ethanol is also subject to limitations of raw material availability. With these limitations, it is doubtful if any of these can be produced on such a large scale as to match the usage of petroleum—though certainly, they can be useful for limited local applications.

A further subtle point about the use of methane, methanol and ethanol as fuels is that, though they are cleaner fuels than petroleum hydrocarbons in that they do not give rise to abnoxious emissions like carbon monoxide and unburnt hydrocarbons, they are not completely innocuous to the environment because they still produce carbon dioxide (CO_2) on combustion. Although CO_2 is no doubt non-poisonous, excess of it—i.e. more than a certain limit of ecological balance—can be harmful. CO_2 has a high absorption coefficient for infrared radiation or heat. Being a heavy gas—heavier than the other constituents of the air—it tends to remain at the terrestrial levels of the atmosphere instead participating in the convection phenomenon which maintains the thermal balance in the earth's atmosphere. The result of this so-called '*green house effect*' is a steady rise in atmospheric temperature (Fig. 3). It has been estimated that the present rate of growth of CO_2 content in the atmosphere could lead to a doubling of it in the period between 2030 and 2050, even after allowing for absorption by the oceans and the counter-veiling effects of vegetation. The result will be a 1.5 to 2°C increase in the *average* global temperature. What is even more disturbing is the fact that this mean increase

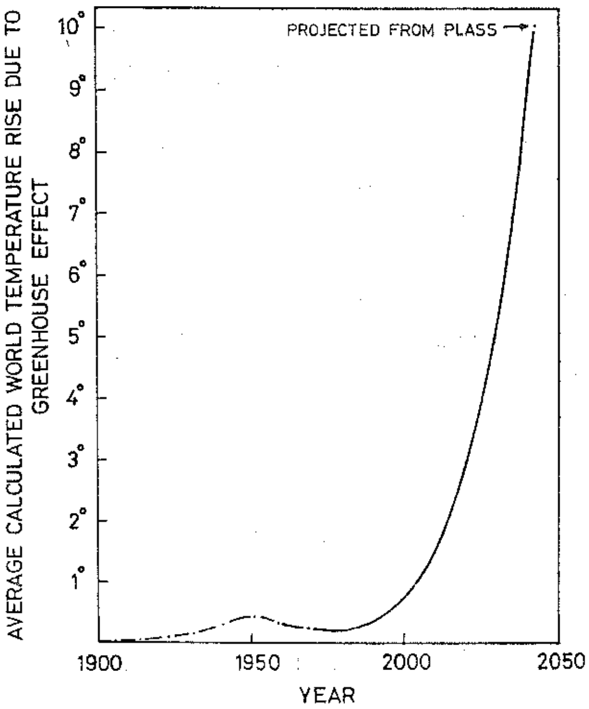

Fig. 3 Greenhouse effect of CO_2. [3]

would be composed of very uneven latitudinal contributions. While in the equatorial regions the increase may be only marginal, it is feared that in the polar regions it may be as high as 10°C, leading to the melting of ice-caps, the rise of the ocean level and other disturbing consequences. Although, admittedly, it is still premature to ring the alarm bell on CO_2, the implications of the green-house effect are such that it is wise to be cautious and to avoid putting too much CO_2 into the air.

THE HYDROGEN ALTERNATIVE

Hydrogen is present in each of the six alternative fuels we have considered so far and is a raw material for the industrial production of at least five of them. It is already being produced on a large scale as a chemical feedstock for the production of ammonia and methanol and in certain processes of petroleum refining. The technology of large scale manufacture of hydrogen is thus well established. At present, 80 to 85 per cent of industrial hydrogen is produced from petroleum hydrocarbons, but alternative technologies are available which are not dependent on the use of petroleum. Though normally it is a gas (one of the so called permanent gases) it can be liquefied. The use of liquid hydrogen as a propellant for big space rockets is well-known. So, the world is quite familiar with hydrogen as a universal constituent of water, petroleum, alcohol and many other things, as a raw-material in chemical manufacture and as an exotic fuel in space research.

Let us now examine, more specifically, the many plus features of hydrogen which qualify it as an ideal energy-carrier, complementary to electricity on one hand and substituting for petroleum fuels on the other.

Hydrogen can be produced in virtually unlimited quantities from the vast water resources of the planet. Excluding processes dependent on petroleum resources, the currently available alternative technologies for the production of hydrogen from water are:

1. Reaction of steam with coal at high temperature, leading ultimately to a mixture of carbon dioxide and hydrogen, from which the latter can easily be separated.
2. Electrolysis of water by passing D.C. electricity through water. Since any form of primary energy can be converted into electricity, it follows that any of the alternative energy sources can be linked to hydrogen production through electrolysis.

Hydrogen is completely odourless, tasteless and non-poisonous. It is freely combustible over a wide range of concentrations (4 to 75 per cent H_2) in air. The product of combustion is water, plus very small amounts of oxides of nitrogen (NO_x) formed by the combination of nitrogen and oxygen of the air at the high temperature of the hydrogen flame. But it is much less than in the combustion of methane or gasoline and, further, it can be minimised to negligible amounts by adjusting the hydrogen-air ratio and other conditions of the combustion. The reproduction of water in the combustion of hydrogen complete the fuel use cycle *Water*⟶ *Hydrogen*⟶ *Water* very quickly and thus ensures the non-depletability of the water resource. This and the almost total absence of harmful pollutants in the combustion-products are the chief virtues of hydrogen as a fuel.

Hydrogen has a higher mass-energy density (energy produced per unit weight on combustion) than any other fuel that we know of (Fig. 4) and, therefore, excels as a power-fuel. Its usability in the existing types of internal combustion engines, gas-turbines and aircraft

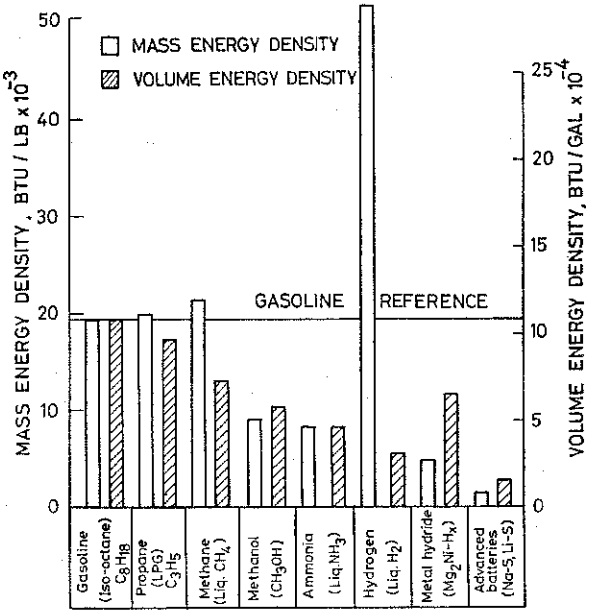

Fig. 4 Energy densities of various fuels. [4]

engines, with only slight modifications in the fuel injection systems, has been amply demonstrated. In particular, it has been shown convincingly that hydrogen can be used with advantage to power automobiles and jet aircraft.

It is obvious that by coupling a hydrogen-powered internal combustion engine or gas-turbine to a generator electrical power can be produced. By carrying out the combustion reaction (chemical combination with oxygen) electrochemically in a 'fuel-cell', electricity can be produced directly and with greater fuel-conversion efficiency, without the intermediate production of mechanical energy, and so without the Carnot limitation.

The simultaneous production of hydrogen and oxygen by electrolysis of water offers greater scope for the use of oxy-hydrogen (aphodid) burners. Direct injection of water into such burners results in a novel compact arrangement (Fig. 5) for the production of high temperature steam for power-generation, obviating the need for boilers. The Apollo space-

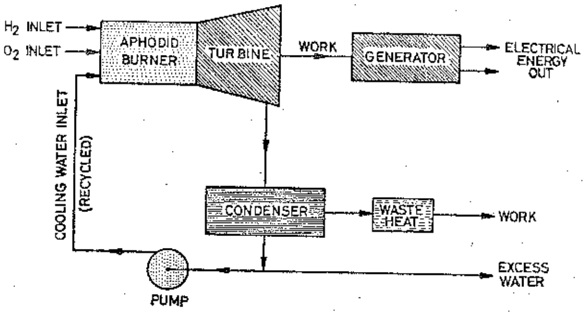

Fig. 5 Aphodid burner for steam generation (General Electric of U.S.A.). [4]

rocket uses an analogous H_2-O_2 rocket engine in its second and third stages. Each engine weighing only 1225 kg and measuring 3.35 m, generates a power equivalent of 2000 MWe, i.e. as much as a superthermal power station. It should be noted, however, that the arrangement requires both hydrogen and oxygen to be fed at high pressure into the burner.

Thus, electricity can be used to produce hydrogen and oxygen from water and the latter can be recombined in an internal combustion engine, fuel cell or aphodid steam-turbine to revert to electrical energy and water. No other candidate fuel offers this reversibility of *Electrical Energy* $\rightleftarrows$ *Fuel.* This unique feature of hydrogen provides a convenient and efficient means for stand-by storage of 'off-peak' electrical power.

Hydrogen can be moved and distributed in steel pipes, just like natural gas. The pipeline system thus provides a capacious storage facility for the gas. Addition of hydrogen to the existing natural gas distribution systems in the USA can make up for deficiencies in the supply of natural gas. It seems that up to 8 per cent H_2 can be mixed with natural gas without affecting the combustion characteristics of the latter and therefore without need for modifications in the combustion appliances.

Pipe-line transport of hydrogen is a means of transmission of usable energy. Fig. 6 shows the comparative cost estimates for transmission of energy as hydrogen in underground pipes and as H.T electricity through overhead and underground cables. It is seen that beyond 250-600 miles (i.e. 400-960 km), depending on the cost of hydrogen generation, it costs less to transmit energy through hydrogen than as electricity in overhead lines. The break-even distance is much shorter (30 miles = 48 km) with underground cables. Besides, the underground pipelines take up much less land area than overhead lines and do not offend aesthetic or environmental considerations. Thus, the interconvertibility of hydrogen and electricity and the more economical transmission of the former over long distances through pipelines make hydrogen an excellent 'running-mate' for electricity.

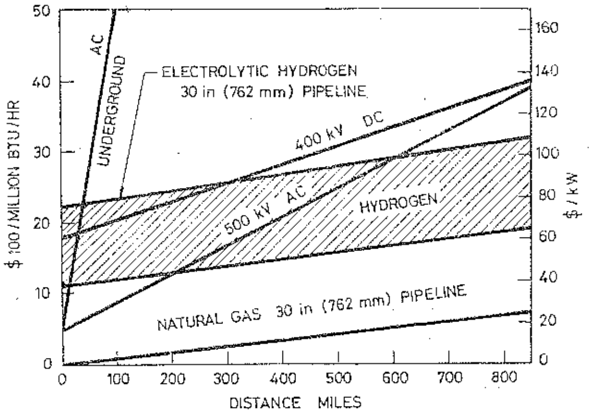

Fig. 6 Comparative cost of energy transmission by Hydrogen and Electricity. [5]

Such an arrangement would ease the design-demands on power-generation. Instead of trying to adjust the generation of power according to load variation, the surplus power can be diverted to an electrolyser to produce hydrogen and thus a uniform level of power-generation can be maintained. It would also relax the necessity to maintain a high standard of reliability of the power-supply because there would always be enough hydrogen storage in the pipelines and elsewhere to allow the electric supply to be interrupted periodically. The flexibility provided by hydrogen transmission also dispenses with the power-synchronization otherwise necessary in A.C. networks.

HYDROGEN AS A THERMAL FUEL

Hydrogen burns with a hot clean colourless flame and can be used as a substitute for natural gas in industrial furnaces, domestic cooking ranges, ovens and other heat raising applications. Only minor modifications are required for adapting the existing types of burners for hydrogen. As hydrogen-combustion produces only water and no offensive gases or smoke to be led out of the work place, chimney-stacks can be dispensed with altogether, resulting thereby in a big improvement in fuel economy. In normal industrial furnaces, it is said that chimney-stacks account for as much as 40-50 per cent of the heat loss. The hydrogen-fired furnace will be just as compact and clean as the electric furnace, but much easier on capital and running costs.

In domestic uses for cooking and space-heating hydrogen offers the unique advantage of flameless catalytic combustion over porous ceramic hot plates topped with a fine dispersion of platinum which catalyzes the combustion of hydrogen even at ordinary room temperature. The gas ignites by itself on coming into contact with the catalyst layer and the plate thus heats up automatically on turning-on the gas. The temperature of the hot-plate can be controlled according to the requirement by regulating the rate of gas flow. The absence of open flames make these appliances completely safe and clean for domestic use. The amount of platinum is usually very small as it is finely dispersed over the ceramic plate and does not add so much to the cost as to be bothered about. However, to promote large scale use of these hot plates and to make them disposable without bothering to reclaim the catalyst material, cheaper catalysts are being developed.

CHEMICAL AND METALLURGICAL USES OF HYDROGEN

One of the noteworthy advantages with hydrogen is that it is already well established as an industrial commodity and is produced on a large scale for use as a raw material in major chemical industries such as ammonia synthesis, methanol synthesis, petroleum refining, hardening of fats, etc. In addition, a number of new uses (apart from its projected use as an energy vector) are in the offing. It will be used in a big way for the production of synthetic hydrocarbons from coal either by direct hydrogeneration or by catalytic reduction of carbon monoxide and in the oxo-synthesis of higher alcohols.

With the reserves of high grade metallurgical coal depleting rapidly, the possibilities of using hydrogen as heating fuel-cum-reducing agent are being explored. Indeed, it has been shown that the direct reduction of iron can be effected very efficiently in compact plants with considerable saving of thermal inputs. Dispensing with the huge blast-furnaces, which are the major sources of thermal, chemical and particulate pollution in steel plant sites, will also be very desirable from the environmental cleanliness and public health points of view.

HYDROGEN ECONOMY CONCEPT

Forecasting the big role that hydrogen is likely to play in the future, some authors have conceived of *A Hydrogen Economy* which envisages hydrogen, economically produced from water with the aid of energy from non-depletable sources, being used as a universal fuel. In residential applications, it would run heating and cooling systems and produce electricity in fuel cells. In transportation, it would run cars either by substituting for gasoline or by fuel-cell electric driven motor systems. In industry, it would replace natural gas. It would have many other uses as a chemical reactant and an ore-reductant in metallurgy.

All these applications of hydrogen, taken together would constitute the Hydrogen Economy, and there is, to look at the matter generally, an advantage in such an economy on ecological and other grounds. It is the only suggestion in which the ease and economy of transmission of energy over long distances is coupled with a great breadth of possible applications and an ecologically sound situation. Thus, the use of hydrogen as a fuel is completely cyclic, for its resource and combustion product are both water and the cycle is completed quickly. Use of hydrogen as a fuel would provide a general solution to air and water pollution problems. Before such an Utopian objective of a Hydrogen Economy can be realized however, there are some basic market problems to be solved. These relate to the production, transmission, storage and utilization of hydrogen and the safety aspects of exposing it to public use. We shall presently discuss each of these aspects one by one.

PRODUCTION OF HYDROGEN

Hydrogen is already being produced on a very large scale for the manufacture of chemical fertilisers and other chemical industries. The current annual world production of hydrogen for these uses is estimated at about 367 billion standard m^3, but the problem is that over 80 per cent of it is derived from petroleum hydrocarbons, which are a fast disappearing commodity.

Fortunately, alternative technologies for large hydrogen production, namely, reaction of steam with coal and electrolysis of water, are available and are, indeed, being used. New processes based on the use of high temperature nuclear heat and solar energy for thermochemical watersplitting are under development in USA, Europe and Japan and may be available for commercial operation by 1990-95.

STORAGE OF HYDROGEN

One of the points on which hydrogen scores over electricity as an energy-carrier is that it can be stored in large quantities for an indefinite period; it does not deteriorate or lose power like electrical storage batteries. There are, basically, four ways available for the storage of hydrogen: 1) as gas at ordinary or slightly elevated pressure, 2) as compressed gas at high pressure, 3) as liquid hydrogen, and 4) as solid metal hydrides.

Gaseous storage: Large quantities of hydrogen can be stored underground in depleted gas and oil fields or in acquifers. These, being sealed by water capillary effect, have been found to be gas-tight for methane, manufactured town gas containing up to 50 per cent hydrogen, and helium and can therefore be trusted to be gas-tight for hydrogen.

However, for many applications, such as for transportation and for container deliveries of the gas, storage in compact forms becomes necessary. This is achieved in, principally, three ways: 1) as compressed gas at high pressures of 200 atmospheres or more, 2) as liquid hydrogen and 3) as metal hydrides. The first mentioned alternative is widely practised for deliveries of comparatively small quantities of gas. It requires heavy steel containers, involves expenditure of energy for compression to high pressure and is inefficient in terms of weight per cent of hydrogen delivered (less than 0.5 per cent). It is totally unsuitable for on-board carriage of hydrogen as fuel in automobiles and the like. However, mention must be made of the recent development of aluminium alloy containers prestressed by steel wire windings outside. It is claimed that these can withstand high internal fluid pressure just as well as steel containers without the weight penalty of the latter.

Liquid storage: Liquefaction of hydrogen is practised on a gigantic scale in the USA for providing liquid hydrogen fuel for space-craft. It is the form that is recommended for hydrogen-fueled aircraft, where its low density and high gravimetric energy density (see Fig. 4) offers a distinct engineering advantage. However, its production is expensive both in energy requirement and engineering costs. On account of its very low temperature (*minus* 253°C), the storage of liquid hydrogen requires super-insulated containers and its handling and distribution require special devices and operational skills. These, however, are not insurmountable difficulties, as transportation of liquid hydrogen by rail and road are common place nowadays in the USA.

Hydride storage: Many metals have the property of absorbing considerable quantities of hydrogen gas to form chemical compounds called metal hydrides. At a given temperature, each hydride is in equilibrium with a definite pressure of hydrogen, which is characteristic of the particular hydride and called its 'dissociation pressure'. If hydrogen is withdrawn from the vessel containing the metal hydride, 'dissociation' of the hydride occurs releasing part of the combined (stored) hydrogen. This enables hydrogen to be stored in metal hydrides as conveniently as in a conventional gas cylinder, with the added advantage of greater storage capacity and much lower pressure. Out of several metals and metal-alloys that have been investigated, an equiatomic alloy (Fe Ti) of iron and titanium, capable of holding up to 2 weight per cent of hydrogen, has proved very popular, particularly for onboard use in automobiles. The Fe-Ti hydride has an energy density of 560 watt-hour per kg, compared to 30 watt-hour per kg for advanced lead acid batteries and 150 watt-hour per kg for lithium-sulphur batteries.

TRANSMISSION AND DISTRIBUTION OF HYDROGEN

The successful implementation of the Hydrogen Economy Concept would depend to a great extent on having efficient pipe-line systems for transmission of the gas over long distance. In the United States, in particular, there is considerable interest to know whether the existing pipe-line systems which have been used for distributing natural gas will be suitable for transporting hydrogen. Although no major problems should arise with regard to the fluid dynamics of hydrogen transmission, serious concern has been evinced about the compatibility of the pipe-line material (steel) with hydrogen, because of the reported proneness of ferrous materials to what is called *hydrogen environment embrittlement.* Researches on this aspect have shown that certain impurities, such as oxygen, carbon dioxide, water-vapour, ammonia and sulphur dioxide, even if present in minute amounts (about 200 parts per million) can severely inhibit and even prevent the occurrence of this form of embrittlement. This makes the fears of hydrogen causing embrittlement failures in pipes largely an academic issue. Optimism in this regard is strengthened by the successful, trouble-free record of several industrial hydrogen pipe-line systems in Europe and USA over the past several decades, such as, for example, the 200 km network of hydrogen pipelines connecting various industries in West Germany's Ruhr belt. Similar networks exist in Texas, USA. Manufactured 'town gas' which used to be distributed in several European towns as fuel gas for homes had 50 per cent H_2 content. No embrittlement has been reported in any of these systems.

SAFETY ASPECTS OF HYDROGEN AS FUEL

It is but natural that the easy ignitability, wider flammability range and explosive nature of hydrogen should cause concern about the safety of on-board carriage and usage of hydrogen as engine fuel. Hence, this aspect has been examined very thoroughly and comprehensively to dispel public fears and it has been established convincingly that, provided proper precautions are taken (and these are quite practicable), hydrogen is no more hazardous than gasoline or natural gas of LPG which are handled quite commonly. Indeed, some of the properties of hydrogen listed in Table 1, render it safer in certain aspects than the other fuels just mentioned. For instance, the lower limit of the hydrogen-air flammability range (4.0) is higher than the corresponding figures for gasoline (1.3) and LPG (2.2). Similarly, the lower limit of detonability of hydrogen (18.3) is higher than for methane (6.3) or petrol (1.1).

Table 1. Combustion Properties of Several Fuels.

	H_2	Methane (NG)	Propane (LPG)	Petrol	Methanol
Auto-ignition Temp., °C	585	540	510	440	385
Min. Ignition Energy, MJ	0.02	0.28	0.25	0.25	-
Flammability limits, Vol. per cent in air	4-75	5-15	2.2-9.5	1.3-7.1	6.7-13.6
Detonability limits in air, Vol. per cent	18.3-59.0	6.3-13.5	-	1.1-3.3	-
Max. Flame Velocity Laminar, cm/sec	270	38	40	30	-
Burning velocity in NTP air, cm/sec	265-325	37-45	-	37-43	-
Diffusivity in air, cm^2/sec	0.63	0.2	-	0.08	-
Buoyant velocity in NTP air, m/sec	1.2-9	0.8-6	-	non-buoyant	-
Stoichiometric mixture, Vol. per cent in air	29.6	9.5	4	1.7	12.3
Mass-energy density (Lower Heat of Combustion), Thousands Btu/1b	51.6	21.5	20	20	9.1
Flame temp. in air, °C	2045	1875	-	2200	-
Thermal energy radiation to surroundings, per cent	17-25	23-33	-	30-42	-

Further, the much greater diffusivity and buoyant velocity of hydrogen (due to its extreme lightness) facilitates its rapid dispersal in the atmosphere, thus greatly reducing the chances of its concentration reaching the lower limits of its flammability and detonability in air, whereas petrol vapour and LPG will linger on and spread horizontally at ground level, posing a very real fire-hazard. On account of its much faster burning velocity combined with its buoyancy, hydrogen fires rise up into the air, rarely last more than two or three minutes and are much less destructive than petrol fire. Moreover, many cases of deaths in petroleum fires are traced to suffocation by the poisonous products of its combustion. These can never happen with hydrogen as the product of its combustion is just water.

Until the 1950's, coal and coke were converted into 'town gas' containing 50 per cent hydrogen, to be distributed through underground pipelines as domestic and industrial fuel. Enormous quantities of hydrogen are produced and handled regularly (often at very high pressures) in chemical plants and, in the United States, several hundred thousand gallons of liquid hydrogen are routinely moved over the railroads and highways, without any fuss, as fuel for the space research programmes.

The foregoing remarks should not, however, be construed as belittling the risks inherent in the fuel-use of hydrogen. The major causes of concern with regard to hydrogen safety are its relatively high proneness to leak (because of its high diffusivity) and the invisibility (non-luminosity) of the hydrogen flame, but suitable means of detection of these have now been developed.

CONCLUSION

The concept of using hydrogen as a synthetic fuel, derivable in the near term from coal and in the longer term from nuclear or renewable energy resources, is attractive for the following reasons:

1. Hydrogen is essentially clean burning, the main combustion product being water. It has a much higher gravimetric energy density than any other candidate fuel and can supplant petroleum and natural gas in practically all areas of fuel usage, with the added significant advantage of freedom from environment pollution.

2. Hydrogen may be substituted for presently used fuels in nearly all applications where a reducing gas is required, e.g. reduction of iron ores.

3. Hydrogen can be converted by chemical processes into a variety of other fuel forms such as synthetic hydrocarbons, methane, methanol and ammonia.

4. Hydrogen can be produced from all terrestrial energy sources, such as nuclear fission, fusion, and geothermal as well as from renewable resources, such as solar and wind energy, ocean thermal gradients etc., by the simple technique of water-electrolysis. Hydrogen production is an attractive form for storage and utilization of intermittent primary energy sources, such as solar or wind power, and also of off-peak power from conventional power-generation systems.

5. Hydrogen can be readily produced from coal, which will be an important fuel resource in the near term; thus hydrogen production makes coal and nuclear energy compatible primary

energy resources, which like electricity, can feed a common energy supply system. It can be delivered at a cost per unit heating value similar to electricity and in some cases, at lower unit cost.

6. Hydrogen can be moved and distributed in steel pipelines without apprehensions about embrittlement. Over long distances, hydrogen offers a cheaper medium of energy-transmission than electricity.
7. Hydrogen can also be stored and transported in condensed form as cryogenic liquid or as solid metal hydrides. These are practical forms for on-board use of hydrogen in aviation and ground-transportation.
8. On safety aspects, hydrogen does not present a serious problem, provided certain precautions, which are quite practical, are followed.

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CALL FOR PAPERS

CONFERENCE ON SOLAR SCIENCE AND TECHNOLOGY organized by the Regional Centre for Technology Transfer (RCTT), an institution established by the United Nations Economic and Social Commission for Asia and the Pacific (UN-ESCAP) will be held at the United Nations Building, ESCAP Headquarters and at the Asian Institute of Technology in Bangkok, Thailand from Monday 24 November to Wednesday 3 December 1980.

It will be co-sponsored by the International Solar Energy Society (ISES), United Nations Educational, Scientific and Cultural Organization (UNESCO), the Asian Institute of Technology (AIT) and other organizations.

The objectives of this Conference are:

1. To expose latest developments in solar energy research and to determine guidelines for research suitable for institutions of higher learning in the ESCAP region,
2. To determine technologies available for immediate transfer in the manufacturing and marketing of solar energy equipment by entrepreneurs in the ESCAP region.

Scientific and technical papers concerning thermal conversion and photovoltaic conversion of solar energy for applications in developing countries especially those in the ESCAP region are called for.

Authors should submit extended abstracts to be reviewed for acceptance. Abstracts should be two pages long, clearly typed on 8½" by 11" paper with margins 1" wide all round ready for photocopying. They should contain: title, author's name and affiliation, text (including tables and figures if necessary), and key references all contained on the two pages allowed. Accepted abstracts will be reproduced and circulated to participants in advance of the Conference. Three copies of each abstract must reach ESCAP by 15 June 1980. The full-length papers, which will be due on the first day of the Conference, will be published in the Conference proceedings.

The Conference will be open to all scientists and technologists interested in the development of solar energy, and there will be no registration fee charged to those participants from governments and non-profit organizations.

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