AN ASSESSMENT OF HYDROGEN AS AN ALTERNATIVE ENERGY RESOURCE

by

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Submitted to the MIT Sloan School of Management in Partial Fulfillment of the Requirements of the Degree of Master of Science in Management

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ABSTRACT

This paper is focussed on the role of hydrogen as an affordable, efficient and environmentally sound technology. In assessing hydrogen's potential role in the future energy economy the popular notion of The Hydrogen Economy is introduced. This paper addresses the energy needs of our future by outlining (1) Hydrogen Technologies, analyzing the (2) Rate of Development of Hydrogen-based Technologies and discussing the potential (3) Rate of Adoption of Hydrogen-based Technologies. The goal of a future safe energy supply will require new and affordable energy carriers (particularly for developing countries), as well as, improved energy utilization techniques to make better use of fossil fuels.

The present energy supply system, characterized by fossil fuel energy technology, is strongly tied to the use of storable and transportable secondary energy carriers. Consumers have adapted to instantly available, convenient energy types. Future energy supply systems will be judged according to whether they can deliver a desired energy service comparable to conventional supply systems and, additionally, whether they will allow developing countries the expansion of their so far insufficient energy supply facilities. Beyond this, attention will have to be paid to the ecological and economic impact of alternative fuel technologies.
Four issues of significance summarize the findings of the thesis research:

(1) Hydrogen is among the most clean-burning, highly-efficiently combustible fuels. Water vapor is its sole by-product emission in combustion and, with sea water as its natural feedstock, it is a permanently renewable resource.

(2) The notion of a Hydrogen-based economy, in its initial stages, would take advantage of the existing infrastructure of the hydrocarbon energy economy, utilizing the energy sources of hydropower and nuclear energy, and gradually accommodating large-scale utilization of solar power. In its final form, the hydrogen economy is expected to require only non-fossil energy sources, assigning hydrogen the main role in a long-term and stable worldwide energy supply.

(3) Major applications of a hydrogen based economy are at least as far away as the middle of the next century. The investments required to produce, distribute and implement hydrogen fuels and hydrogen fuel technologies are so large and all-encompassing that the transition to a hydrogen-based economy would clearly have to be spread over many years. Physical limitations and economies of scale restrict its short-term direct utilization as a gaseous or liquid energy carrier, as well as, its use in the manufacture of synthetic natural gas and synthetic liquid energy carriers from coal, tar sands and oil shale. Because total lead time for establishing efficient and large-scale conversion facilities is very long, most of the first major uses for hydrogen will involve captive, rather than merchant hydrogen technologies.

(4) Components of the hydrogen economy cannot be expected to be adopted in the event that they fail to yield a Return on Investment comparable to alternative uses of capital. It is, therefore, most likely, that hydrogen technologies will be introduced to and adopted by smaller niche markets - for example, first in self-contained, small-scale industrial regions or in parts of the commercial aviation sector.

The multiple sources of authors and scientists cited in the Bibliography are indicative of the extent of decades-long, increasingly world-wide research that has been, and will continue to be conducted by the scientists in government and industry who are optimistic about hydrogen's role in fueling our future.

Thesis Supervisor: Michael A. Rappa
Title: Assistant Professor of Management
This thesis is dedicated to

the support and patience of my parents and family

the need to address the indifference of consumption of the earth's human family, and

to the personalities of my inspiration, in part, the characters of *The Fountainhead* and *Atlas Shrugged*, who as a productive and independent minority in the course of history forge the future of civilizations.

(and as detailed in the principles of *Objectivism* by Russian emigrant and author - Ayn Rand.)
"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable... I believe, then, that when the deposits of coal are exhausted we shall heat and warm ourselves with water. Water will be the coal of the future."\(^1\)

Jules Verne, ca. 1870

The Mysterious Island

\(^1\)Secondary Source, Economies of Hydrogen Fuel for Transportation and Other Residential Applications, Proceedings of the 7th Inter-Society Energy Conversion and Engineering Conference, San Diego CA, American Chemical Society, Wash. DC, 1972, p. i
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Energy is needed as heat for industrial processes, heating purposes, cooking and producing warm water, a power for stationary and mobile engines, as well as for lighting and communication. By far the largest proportion (70 to 80%) goes to heating supply. For that, fossil fuels - coal, oil, and gas - are used. In developing countries non-commercial biomass (firewood, plant wastes, manure) is the most important source of low-temperature heat. Stationary motive power, lighting and communication are the domain of electricity. In the transport sector liquid hydrocarbons are used most exclusively, with the exception of electrified railroads.  

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I. Introduction

My interest in the energy economy was motivated both by an interest in analyzing the technologies servicing the world's energy consumption and demand requirements, as well as, by an attempt to educate myself and, in turn, the reader in regard to the viability of a permanently renewable and environmentally superior alternative to the entrenched and pollutant hydrocarbon fuels presently in use. Hydrogen in many respects is an ideal alternative energy resource in that it is both abundant and non-pollutant; the perspective of this paper, therefore, has as the focus of its analysis the concept of "the hydrogen economy", which presumes the eventual complete substitution of hydrocarbon fuels for hydrogen technologies.

The applications of hydrogen technologies are all-encompassing, including all sectors of the world economy reliant on the direct production, distribution and even consumption of energy. The intent of any analysis addresses the environmentally-conscious and technical layman, rather than opportunity-seeking business persons or innovation-oriented scientific researchers, in an attempt to describe in very general terms the potential role which hydrogen could have in fueling the economy of the future. In that regard, I have structured the paper by organizing the analysis within the auspices of the principal sectors of potential hydrogen application - industrial chemical processes, gas and electric utilities, and transportation fuels. In that regard, I begin the analysis by introducing the multiple uses of hydrogen technologies, followed by an overview of research developments related to hydrogen technologies applied to the above mentioned sectors. I conclude by presenting a speculative analysis of the potential rate of adoption of various hydrogen technologies in industrial and commercial sectors, with particular attention to the responsible participation of governments in influencing the adopted energy fuels of our future.

The concept of the hydrogen economy is many decades old and spans the efforts of researchers in several different countries. For this paper, I have relied for my research predominantly on the presentation of two technical sources - Hydrogen as an Energy Carrier: Technologies, Systems, Economy translated from German and edited by Carl Joergen Winter and Joachim Nitsch and Energy, Vol. II, Non-Nuclear Energy Technologies, by S. Penner - both writings were chosen due to the encyclopedic character of the technological and process analyses they present. A less objective perspective of the potential of hydrogen is provided by Edward Dickson in The Hydrogen Energy Economy: A Realistic Appraisal of Prospects and Impacts which I both appreciated for its conclusions, often noted in this paper, but, at the same time, have enjoyed modifying in terms of my own interpretations of hydrogen's future in the world's energy supply. It is relevant to mention that I have had several hundreds of sources from which to choose in beginning to assess hydrogen's development and potential as a viable commercial entity. Rather than develop an in-depth analysis of an isolated application of an emerging technology, I have attempted in this thesis instead to emphasize the diversity of applications of a
research topic complicated by its many participants and to, in turn, present an educational and enjoyable reading, assessing the commercial boundaries of an as yet largely ignored energy resource - hydrogen.

i. The Chemical Properties of Hydrogen

Hydrogen is not a primary energy resource. Hydrogen is as an energy form or carrier because it requires a primary energy resource to produce it and because it provides a means to transport and store energy derived from other sources. Hydrogen can be produced from water and hydrocarbon fuels by thermo- or electrochemical processes. Hydrogen's most significant primary resource is obtained thru electrolysis from water, the world's most abundant natural resource; as a fuel, hydrogen can be used to generate electricity either by combustion or in a device called a fuel cell.

Hydrogen is a colorless, odorless, tasteless, and non-toxic gas. Pure hydrogen flames are invisible and smokeless. Stationary hydrogen flames produce some acoustic noise - greater, for example, than for an unignited gas flow. The buoyant and diffusivity properties of hydrogen help decrease the hazards associated with hydrogen leakage. These same properties, however, increase the difficulty of determining the precise location of a hydrogen leak. Hydrogen is an exceptionally clean-burning fuel: when it burns in air, with very high energy release per unit mass, the only major reaction product formed under suitable conditions is water. Natural precipitation would recycle water between consumption and production.

ii. A Brief History of Hydrogen Technology

In the past, hydrogen has been produced for the following purposes: as refinery feedstock in the petrochemical industry for the production of plastics, foodstuffs, rubbers, and pharmaceuticals; as a reducing agent in metallurgical processing and in scrap-metal recovery. Until the middle of the twentieth century, manufactured gas, town gas, and coal gas (all hydrogen-rich (typically 50% hydrogen content) gases) were widely distributed in the US by low-pressure pipelines. Natural gas has almost completely replaced manufactured-gas in the US, although manufactured gas is still used in Europe. In 1945, nearly 80,000 miles of gas main were in use for distributing manufactured gas. There has also been an assortment of specialty applications, such as the use of hydrogen in space-booster rockets.

One drawback to hydrogen as a fuel is concerned with storage because the energy content per unit volume for hydrogen gas is very low and because the handling costs for highly-compressed gases are very large. Analogous to electricity in as far as its role as an energy carrier, hydrogen has many similar characteristics of an ideal fuel. Hydrogen might assume a "common denominator role" in the portable fuels arena analogous to the use of electricity, a common denominator energy form in stationary applications. (Gasoline is an example of a
common denominator fuel for cars in that it fuels cars of all makes irregardless of design or origin. 
Ultimately, the degree of interchangeability between forms of hydrogen and electricity provides a likely basis for future economic, technological and environmental benefit thru the commercial adoption of hydrogen energy technologies.

iii. **The Hydrogen Economy**

As concluded by Dickson, et al in their encompassing analysis of the hydrogen economy, three conclusions can be made in regard to the economics of a hydrogen-based economic system. First, by definition as a secondary form of energy, hydrogen must cost more than the primary or secondary energy forms from which it is derived. Second, alternative fuel market competition will, in the long run, balance the unit cost of various forms of energy i.e., it is unlikely that the cost of hydrogen could undercut the price of its major (primary) fuel competitors. Third, ignoring the relative cost factor of alternative fuels (which, in the short run, would delay interest in a (permanently renewable resource) hydrogen economy), the time when hydrogen implementation could reach a significant scale is distant. Finally, it is to be expected that the hydrogen energy economy concept would not develop without strong synergisms developing between it and the hydrogen chemical economy. (For an overview of a hydrogen and non-fossil fuel energy system, please see Appendices 1 - 2)

The concept of combining hydrogen fuels with electricity generating facilities in the future energy economy is technically feasible because hydrogen could replace petroleum or natural gas in essentially every application. Because of the long lead times required, even a vigorous program to promote hydrogen use could not make a significant contribution to U.S. energy independence before the year 2000. Massive investments in the production, distribution and storage of today's fuels pose a very significant barrier to a rapid voluntary conversion to a hydrogen economy. The worldwide requirements of almost $9 \times 10^9 \text{tce/year (1986)}$ for fossil fuel energy of high energy density in solid, gaseous or liquid form can be stored, naturally or technically over almost any length of time without loss. In addition, its transportation across continents and oceans by ship, rail, road or pipelines is everyday practice and runs more or less smoothly. In contrast, hydrogen storage and transmission forms are not yet competitive - cryogenic-storage facilities, for example, are at present prohibitively high.

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iv. The Energy Industry

While systems based on synthetic fuels from fossil resources would be easier to implement in the structural framework of today's energy infrastructure, they can only be a temporary solution, followed by the need for yet another transition in the future. In this respect, hydrogen offers a clear advantage over synthetic gasoline, diesel, methane, and so on, because ultimately the concentrated carbonaceous resources on which these synthetics are based will, unlike hydrogen-based water and solar resources, be in short supply. Hydrogen although it could replace petroleum products or natural gas in essential every application is less easily (more hazardously) transported, has low energy per unit volume, is more difficultly stored, and is incompatible with existing liquid fuel distribution systems.

Petroleum and natural gas supply most of the world energy requirement largely by virtue of the fact that they are easily transported in liquid or gaseous form, have high energy content per unit weight and volume, and are easily contained. Distribution of total energy consumption in industrialized countries by sector is about 30 to 40% for industry, 20 to 30% for transportation and 30 to 40% for households and small consumers (including, public facilities, trade, business, other service industries and agriculture). In less developed countries, on the other hand, the last sector, households and small consumers, dominates at a rate of up to 80% - depending on the degree of industrialization and the development of transportation in a given country. 4 (For an overview of world energy consumption, please see Appendices 3 - 5)

v. Expectations for the Future

Experience gained in the non-energetic (synthesizing chemical compounds) and indirect energetic (metallurgical reduction reactions to upgrade fossil energy carriers) utilization of hydrogen has profoundly influenced the development of hydrogen technology - in particular, production and safe usage. Energy conservation measures such as improved conversion efficiencies, improved end-use efficiencies and reduction of wasteful practices will undoubtedly (and, in fact, already) play an increasingly role in the energy sector. Extended development of petroleum and natural gas supplies by tertiary recovery, discovery and development of outer continental shelves and under the sea, discovery and development in remote land environments can also be expected.

The world depends almost entirely on fossil fuels, especially petroleum, natural gas and coal and largely because in the case of the first two they are easily storable and transportable. The dynamics of the energy sector are,

therefore, of principal importance in terms of predicting the structure and consequent changing demands and sources of supply of future energy sources. In that regard, the following trends are of particular relevance:

(1) As basic energy sources multiply so will a multiplicity of energy storage and carrier mediums and techniques be developed. (Examples include, the production of synthetic liquid fuels from unconventional hydrocarbons - oil shale and tar sands, increased use of nuclear fission reactors for electricity generation - conventional water-cooled, high-temperature gas-cooled and breeder reactors, and the development of nuclear fusion technologies - magnetic confinement of plasmas and laser-induced.)

(2) Basic energy resources will be beyond the political influence or protection of the U.S. government - giving rise to public sentiment favoring energy alternatives that would offer independence from foreign control. (This will encourage an increased reliance on coal of various grades for direct combustion, liquefaction into portable fuel, and gasification into pipeline-quality fuel, the increased application of solar energy in many direct and indirect forms - sunlight, wind, falling water (hydroelectric), ocean temperature differences, and biomass grown for uses as a fuel, and the generation of electricity from geothermal energy - natural steam and hot water reservoirs and dry hot rock.)

(3) Increasing emphasis in both industrialized and lesser-industrialized countries can be expected to be placed on environmental quality, especially as it relates to energy production and end-use. (This will, in turn, encourage the development of conservation technologies and the more efficient utilization of carbonaceous wastes - municipal and industrial, forest and agricultural and sewage sludge.)

(4) Deposits of carbonaceous materials of fossil origin will become physically exhausted as others become increasingly uneconomical to recover. (This will mandate the adoption of renewable energy resources - which include hydrogen, in addition to geothermal, solar, water, and wind energy technologies.)

(For energy terminology interpretation during the readings, please see Appendix 6)
II. **An Analysis of Hydrogen Technologies**

The time scale for the evolution of technological change varies greatly depending upon the technologies involved. Some technologies have caused great change in just a few decades (examples include, personal computers, jet-powered commercial aviation and transistors). Other technologies have very long developmental lead times or deployment schedules, and, consequently, develop slowly or become important only long after the technology is originally conceived - for example, electric power, video telephones, and space travel. My primary objective in addressing the energy resources available is the complete (and permanent) substitution of hydrogen fuels for fossil (non-renewable) fuel utilization so that I have included renewable energy sources such as hydro, solar or nuclear energy facilities in the analysis. An assessment of the suitability of hydrogen as a universal energy source entails an analysis of its total heat content, as well as of those combustion parameters (kinetics) that determine ease of use in such non-conventional applications as, for example, in boilers, transportation systems, space heating units, etc.

Hydrogen is chemically very reactive and, therefore, not found in its elemental state on Earth. Combined chemically with other elements, it is virtually omnipresent in such forms as water (the most abundant hydrogen resource), fossil hydrocarbons (coal, petroleum, natural gas, and oil shale), biological materials (carbohydrates, protein, and cellulose), and minerals (such as bicarbonate rocks). Energy must be supplied to release hydrogen from any of these compounds in order to break the chemical bonds. Most of the hydrogen currently is made from natural gas by reaction with steam and oxygen or air - a process called "reforming". Hydrogen technology is most well-established in such different areas as space flight, hardening of fats, microelectronics and fertilizer production. Conventional applications include those involving large-scale current use in industrial processes such as ammonia and methanol synthesis, petroleum refining, hydrotreating and -cracking, coal conversion to liquid and gaseous fuels, oil-shale conversion to liquid and gaseous fuels, iron-ore reduction and process heating.

i. **Hydrogen Combustion and Thermochemical Properties**

Composition limits in which a fuel-air mixture is capable of burning are a function of the conditions of various combustion applications. Hydrogen's chemical properties as a combustible fuel make it superior to conventional fuels, gasoline and natural gas, insofar as desirable properties for combustion of fuel-air mixtures - clean burning, flame speed, flammability limits, and quenching distance - are concerned. (Please see Appendix 7)
Clean Burning

Hydrogen is extremely clean burning and, therefore, completely avoids both environmental regulatory constraints and the problems of sediments and corrosion on turbine blades caused by residues and ash particles from liquid fossil fuels that, together with compressed air, get into turbines.

Flame Speed

Hydrogen-air mixtures support exceptionally high flame speeds, allowing the use of small combustion chambers.¹⁵ (Flames are more difficult to blow off a flame holder when the gas-flow speed is increased.) At the same time, hydrogen's efficient burning capacity makes it more difficult to quench - in the event of detonation, or explosion.

Flammability Limits

Hydrogen has exceptionally wide combustible (flammability) limits in air-fuel mixtures. These limits are dependent on temperature and atmospheric pressure. Minimum ignition energy is seen to decrease rapidly (for all gas compositions) as pressure is increased (chemical reactions accelerate with pressure) but, in the case of hydrogen, the flammability limits become appreciably wider when compared with other gases as the temperature is raised.

Quenching Distance

Hydrogen's versatility as a combustible fuel is evidenced in its very small maximum quenching distance. The quenching distance is defined as the maximum distance between two parallel plates which are imposed in order to control the combustion process by confining gases to the immediate vicinity of two surfaces. The fact that the maximum distance is much smaller for hydrogen than for other fuels means that hydrogen combustion compared with that of other fuels is not only easier to initiate (with lower energy) it is also more difficult to quench - and thus both easier to maintain and more difficult to extinguish.

---

ii. **Hydrogen Production**

Hydrogen-based manufacturing technologies include nuclear fission electric generation, thermochemical water splitting, coal gasification, liquefaction and electrolysis.

ii.i. **Fossil Fuel Hydrogen Production Technologies**

Given today's technical and economic conditions, "hydrogen production from natural gas, naptha, and heavy oil is superior to processes based on either electrolysis or the gasification of coal." 6 With the exception of water, all (hydrocarbon) raw materials used for hydrogen production contain sulfur which acts as a catalyst poison in the various steps downstream process manufacture, so that the materials must be de-sulfurized either before they enter the process, or the process gas has to be de-sulfurized after the primary reaction (transformation with steam and oxygen). Conversion efficiencies range from 72% for natural gas to 76% for heavy oil and 60% for coal.

**Coal Gasification**

Hydrogen obtained from coal is generally agreed and expected to be the lowest-cost large-scale source of hydrogen in the near future. Coal gasification was developed years ago but is only recently being deployed in modern large commercial plants; however, these applications have been directed at producing not hydrogen, but methane for use as a substitute natural gas. Low volatility and high sulfur content of heavy oil prohibit steam reforming of this feedstock so that it is treated autothermically in a flame reaction by adding steam and oxygen in a partial oxidation at 1300 to 1500 °C (Celsius). Similar to heavy oil, "the gasification of coal is only autothermic by treating the coal with oxygen and steam at 1400 to 1600 °C. The gasification occurs either in a fly ash flame, a moving bed, or a fluidized bed. Using present technologies, hydrogen would be more economically manufactured in the hydrogenation steps in oil shale processing and the production of methanol from coal and various waste materials." 7 It appears that, although coal gasification and liquefaction technologies will eventually be deployed requiring hydrogen, the hydrogen will be derived from the energy of coal itself - and not from a merchant hydrogen, such as nuclear power-produced hydrogen.

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Electrolytic Hydrogen Production Technologies

Relatively little hydrogen has been produced commercially by electrolytic processes (ca. 3% of 1975 total U.S. production of hydrogen), because for decades when large quantities have been needed it has been more economical and more convenient to obtain hydrogen by reforming methane or oils. Commercially available electrolysis cells operate in the range of 60 to 70% efficiency - much of the energy is dissipated in driving the electric current through the cell and appears as heat. (Please see Appendix 8) Potential improvements in efficiency, noted by Penner, are expected through a cell's ability to produce gaseous electrolysis products with heat absorption from the surroundings are responsible for experimental energy-conversion efficiencies during electrolysis greater than unity. It is possible to improve the efficiency of electrolysis to about 100% because, under optimal operating conditions, the theoretically-attainable energy conversion by electrolysis is about 120% of the electrical-energy input.

At present, steam electrolysis is still relatively far from technical maturity whereas alkaline water electrolysis and membrane electrolyzers are offered commercially by a considerable and rising number of manufacturers. In addition, the future availability of catalytic materials for electrolytic cells is of critical importance. Only alkaline water electrolysis has any chance of being used in large-scale electrolytic hydrogen production facilities. One of the most attractive attributes of electrolytic production is the small size of the practical cell. In other words, plant output could be tailored to virtually any level of output without sacrificing important economies of scale. Catalytic materials include platinum and nickel. In commercial applications nickel compounds are the most likely future catalyst of choice - it is, however, not a very abundant metal, and the United States currently imports about 70% of its needs (58% from Canada). Supply is further restricted by competing demands on nickel availability - for example, for the production of high-strength steels and other alloys.

Thermodynamic Hydrogen Production Technologies

Thermochemical Processes

Thermoelectric power conversion occurs in a closed-cycle in order to maximize efficiencies by containing heat energy generated by high-temperature (2000 °C/3600 °F (Fahrenheit)) reactions. The process, outlined by Dickson, et al, depends on several chemical reaction steps whereby water can be broken into its hydrogen and oxygen components with all the other, intermediate reactants being continuously recycled. Energy conversion efficiencies are less than 20%, but potentially approaching 60% which would make hydrogen production less

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energy consuming and possibly less expensive as well. A serious drawback to the closed-cycle thermochemical production process lies in the expected loss (leakage) of reactants in the multi-step cycle process. The loss of a small fraction per cycle would release large amounts of reactants - some of which such as mercury, have considerable environmental consequences. (Please see Appendix 9)

Thermoelectric energy conversion involves the "liberation of electrons from an emitting surface under the influence of heat addition and is described by the combination of the Seebeck (voltage difference generated when two different metals are heated to different temperatures), Peltier (the ratio of the heat change to the current flow at the junction of two dissimilar metals) and Thomson (the ratio of the heat change per unit current flow to the local temperature when current flow through a wire supporting a temperature gradient) effects." 9 The freed electrons migrate to a collector against retarding forces. At the collector, the electrons lose some of their energy by heating and pass subsequently through an external load. Existing thermal gradients may be created by application of abundant energy sources (e.g., nuclear-breeder or fusion reactors, solar or hydro energy facilities).

Thermonuclear Processes

Nuclear energy may be used to support a very large number of sequential chemical reactions at temperatures below about 1,000 °K (degrees Kelvin) which have the effect of producing hydrogen and oxygen from water. With high-powered lasers in a laser fusion reactor - the process uses neutrons produced in the fusion reaction to produce hydrogen by "radiolytic disassociation". The sequential reactions are easily performed in separate reaction steps; however, while there are theoretically no chemical losses, the use of mercury and of corrosive HBr constitute significant potential hazard and control problems. Furthermore, for each pound of water processed, more than 110 lb. of other materials are required in the combined nuclear-reaction sequence.

Photovoltaic Cells

Although costly, photovoltaic power constitutes a standard energy source in space vehicles. Photovoltaic power conversion involves the direct production of electricity in suitable solid-state devices (solar cells) on absorption of solar radiation. As described by Penner, a solar cell "is constructed from a semiconductor (such as silicon or germanium) by doping the semiconductor material to produce n-type (negatively charged carriers are released on doping the silicon matrix) and p-type (characterized by a deficiency of electrons and, therefore, effectively labile positive charges) slices." 10 The theoretical efficiency of solar cells varies as a function of the multiple materials available for their construction. Semiconductor materials should have low reflectivity and should not

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10 Ibid, p. 308
interfere with the penetration of the incoming solar radiation to such depths that hole-electron pair creation (desired power generation) can be readily accomplished. For example, silicon solar cells are seen to be capable of higher current densities whereas gallium-arsenide cells show larger voltages. Similarly, the different materials vary in their respective power output per unit weight - a function of cell thickness and energy carrier lifetime. There is, in addition, a well-defined minimum thickness of the cell wall plates above which the conversion of a solar cell has diminishing efficiency.

Fuel Cells

Intensive research and development efforts have confirmed that the most efficient electrochemical reaction of fuel and oxidizer for the direct generation of electricity has been achieved with a hydrogen/air reaction in a fuel cell. (Please see Appendix 10) Authors Winter and Nitsch consider the future large-scale use of fuel cells inseparable from hydrogen-based energy technology. In other areas of research, chemical engineers and electrochemists are trying to produce hydrogen from hydrocarbons, hydrous solutions or water in a pure and economic form and to reconvert it using highly efficient fuel cells. Advanced fuel-cell development has been funded primarily for space applications while proprietary programs for various industrial laboratories have received attention only as a function of available investment monies. The need to provide electric power aboard manned and unmanned spacecraft has, in particular, led to the development of fuel cells - which have eventually also found practical applications, such as in small power stations and for a variety of purposes in addition to its utilization for transportation.

The complete fuel-cell system generally contains a reformer for fuel processing and in inverter to convert the d.c. fuel-cell to a.c. connected in a series of low-voltage devices. The basic reaction is catalytic oxidation of hydrogen rather than combustion; the end product is water and some heat and accomplishes the direct conversion of chemical energy into electrical energy such that the heat of reaction that is normally released by the combustion processes is directly converted to electrical energy at low and moderate temperatures. Hydrocarbon-air fuel cells have overall efficiencies of between 40 and 50% at minimal power output (20 kw (kilowatt = 10^3 watts)) while hydrogen air and hydrogen -oxygen fuel cells have 55% and 60% efficiencies, respectively. Theoretical efficiencies could, however, exceed 80%. (Please see Appendix 11) Fuel-cell systems are not significant sources of air and thermal pollution and currently have primary appeal as low-output power sources (10 to 200 kw) in remote areas and as topping cycles or supplements (25 to 100 Mw (Megawatt = 10^6 watts)) in central utility-station operations. Furthermore, commercially viable fuel-cell systems do not show the

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rapid decrease in efficiency with decreasing power output that occurs for other types of electricity-generation units.

**Monocrystalline and Multicrystalline Fuel Cells**

Winter and Nitsch presented substantial materials on fuel cell technologies which I have in shortened form included in this and the following section. Given that the energy requirement for production of thin-film solar cells is only about 10% that of crystalline silicon solar cells, and including assured life time expectancies of 20 to 30 years, it can be expected that thin-film solar cells will be more cost-effective in terms of electrical output than crystalline solar cells. Based on silicon with the highest level of purity, so-called electronic grade silicon, mono- and multi-crystalline silicon is produced from single-crystal cylindrical rods (by pulling crystals from a melt and from cast multi-crystalline blocks (sawn into disks)), or directly from mono- or multicrystalline sheets. The current state of development of monocrystalline solar silicon cells is such that commercially application is poor, achieving conversion efficiencies between 8% and 12%, increasing at best to 15%.

**Thin-Film Fuel Cells**

Thin film technology uses direct semiconductors for photovoltaic energy conversion thereby reducing the thickness required for the absorption of solar radiation. The methods to deposit such thin layers (various types of vacuum deposition technologies, high-frequency sputtering, chemical vapor deposition, plasm-enhanced deposition, screen printing, spray-on technology) differ in their technological and energy demands. Gallium Arsenide, although appealing due to its excellent semiconductor properties, is an expensive substrate material such that even if used at low purity levels it will increase overall costs of solar cells considerably.

iv. **Synthetic Hydrogen Production Technologies**

Because of the combination of storage difficulties of hydrogen gas and liquid, as determined by hydrogen's low energy content of per unit volume and the largely untried large-scale applications for hydrogen distribution technologies, a variety of synthetic hydrogen compounds have been considered as alternative fuel sources. These alternative fuels include a hydrogen/natural gas mixture, methane, methanol, ethanol, ammonia, and hydrazine.

The case for methanol is of particular interest. Up to 30% of methanol may be added to commercial gasolines without modification of the internal combustion engine while, at the same time, improving engine performance and mileage and lowering emissions. Methane, methanol and ethanol are, however, carbon-containing compounds and, therefore, perpetuate the problem of carbon monoxide as a combustion by-product. The remaining fuels, though maintaining individually attractive properties, retain, at the same time, particularly
unappealing characteristics. While hydrogen could possibly first be mixed with natural gas for general use, in order to retain its ideal chemical properties discussed above, hydrogen would ideally be distributed in a pure form during prototype evaluation. Ammonia has a disagreeable odor and is a toxic gas under normal conditions. Hydrazine, though it has exceptionally favorable physical properties since it is a liquid at room temperature, is a highly toxic material. Complete removal of nitrogen oxide from the combustion products of ammonia and hydrazine might prove more difficult than for hydrogen itself. Adopting ethyl alcohol as a primary energy source for transportation would necessitate developing an entirely new distilling industry.

iii. **Hydrogen Storage Technologies**

The four most important technologies that complement hydrogen energy storage systems are cryogenics, metal hydrides, electrolysis, and fuel cells. For short-term storage of energy, as might be employed by either an electric utility or in some solar energy collection systems, there are many technologies competing with hydrogen technologies. These include pumped hydroelectric, compressed air, magnetic fields in superconducting solenoids, advanced concept flywheels, underground storage of hot water, advanced high-energy and power density batteries.

i. **Gaseous Hydrogen Storage Technologies**

Safe storage and handling of both gaseous and liquid hydrogen requires implementation of the following operating conditions: adequate ventilation in all operating areas, prevention of hydrogen leaks, purging of all storage and handling systems before and after hydrogen use, elimination of confinement for large quantities of gaseous or liquid hydrogen, avoidance of oxygen or air contamination, and total elimination of all possible ignition sources. The development of storage systems of hydrogen compounds with low decomposition temperatures will provide acceptable long-term solutions.

ii. **Liquid Hydrogen Storage Technologies**

There are only three practical methods to distribute and store hydrogen for liquid use - each of which is awkward compared with the other fuel options: as a pure liquid, in the form of metal hydrides, or in the form of hydrogen-containing chemical compounds. During transfer of liquid hydrogen from one cryogenic storage vessel to another, there is unavoidable boil-off - which when combined with the reliquefaction required at several transfer points would offset any gains in engine efficiency. Liquid hydrogen is transported and distributed in cryogenic truck trailers and rail cars. The truck trailers typically carry 7,000 gallons (2.1 x 10^8 Btu (British Thermal Units)) while rail cars carry up to 34,000 gallons of liquid hydrogen. Liquid hydrogen pipes and tanks must be purged with either hydrogen or helium to remove sources of air. (Please see Appendix 12)
Hydrogen Transmission and Distribution

Material compatibility with a hydrogen environment in the forms of hydrogen or hydrogen-environment embrittlement may be a significant obstacle to future hydrogen transmission networks. Hydrogen embrittlement is described by the fact that "molecular hydrogen is dissociated at the surfaces and atomic hydrogen then penetrates into the lattice structure of steels indicating that conventional natural-gas pipelines may well be corroded by hydrogen. The phenomenon leads to a loss of ductility and to stress cracking, blistering, or flaking. Hydrogen-environment embrittlement has been characterized by moderate to severe corrosion in hydrogen-fuel operations at the National Aeronautics and Space Administration (NASA)." 12

Gaseous Hydrogen Transmission and Distribution Technologies

Existing natural gas regulator stations are compatible with hydrogen use although it is likely that major portions of the existing terminal distribution lines will have to be replaced when pure hydrogen is used. Distribution networks typically contain city-gate regulator stations at the transmission-line connections and district regulator stations throughout the network. While many natural gas networks utilize large diameter cast-iron mains originally designed for low-pressure manufactured gas distribution in downtown areas, suburban networks are usually constructed of welded steel pipe or, more recently, plastic pipe. As researched by Penner, there is a problem in both the significant hydrogen permeability of some plastic pipe compounds and what is known as the reverse Joule-Thompson effect whereby there is a slight temperature rise of hydrogen expansion at regulator stations. (Natural gas and most other gases are cooled on expansion.)

Liquid Hydrogen Transmission and Distribution Technologies

Penner estimates that alone the capital costs portion of liquid transmission pipelines is 25 times larger than the corresponding total cost for transmission of gaseous hydrogen. Nevertheless, transmission of liquid hydrogen would probably be preferable to gaseous transmission because of the fact that liquid-hydrogen storage facilities are more easily sited than gas-storage facilities. Also, liquid hydrogen is in contrast to gaseous hydrogen directly suitable for such end uses as transportation applications.

v. **Hydrogen Technology Applications**

Hydrogen technologies have already been adopted as fuel in automotive vehicles, in boilers, in aircraft-turbine and piston engines, where gasoline and/or natural gas are customarily applied. Provided necessary and acceptable modifications are made in the equipment used, hydrogen is easier to use economically than conventional fuels as a result of its higher flame speed in hydrogen-air mixtures, its lower ignition energy, wider flammability limits, and lower polluting combustion properties. Chemical applications, such as, converting hydrogen for specialty applications into more easily manageable compounds such as ammonia, methane, and methyl alcohol) also merit consideration, although some of these conversions cannot be accomplished without losing the considerable advantage of burning pure hydrogen or relieving the pressure on carbonaceous deposits for energy applications.

i. **Energy Utilities**

In nearly every end-use sector, hydrogen faces strong competition from alternative fossil-fuel-based technological options. (For a description of the sources and application of alternative energy technologies, please see Appendix 13.)

**Gas Utilities Applications of Hydrogen Technologies**

Both the consumer and the utility have a vested interest in substitute natural gas (methane SNG) in preference to hydrogen. The SNG strategy allows the gas industry to confined all transitional changes to the gas production end of the gas business and to leave intact its present large investment in natural gas delivery systems. In other words, the consumer need not change any equipment, appliances, or habits in order to accommodate the changeover in fuel. Conversion to hydrogen would require change of much of the distribution systems as well as consumer appliances.

**Electric Utilities Applications of Hydrogen Technologies**

In energy and electricity production processes the use of the correct burner design is crucial in accommodating the unique kinetic properties of hydrogen fuel - a factor which would significantly contribute to capital costs in adapting present plant and, in particular, distribution networks to a hydrogen-based system. For space-heating applications, venting may not be essential unless the high humidity associated with water production proves problematic. Hydrogen may be distributed readily i.e., by conventional methods already in use to households for use in space-heating and cooking units. The preference of hydrogen for electricity generation in fuel cells has already been discussed.
ii. Transportation Fuel

Though there does not seem to be much advantage to or incentive for the use of hydrogen in large ships since ships are fuel either by a low-grade heavy oil (bunker fuel) or by diesel, there are significant synergies for hydrogen technologies in both automotive and aeronautic applications.

Automotive Applications of Hydrogen Technologies

In automobiles, carburetors must be modified and ignition timing must be adjusted. In internal-combustion engines, burning at preferred mixture ratios may require increased crankcase ventilation. Diesel engines should be easily adapted to hydrogen use.

Aeronautic Applications of Hydrogen Technologies

For aircraft applications liquid hydrogen is vastly superior to conventional jet fuels because it can be used en route to the engines to cool the aircraft skin, which is heated by aerodynamic drag. For long-range space mission, hydrogen is the fuel of choice because of its large energy content per unit mass. Liquid hydrogen is, in fact, an essential fuel for spacecraft but this single use constitutes by far the largest contemporary market for merchant hydrogen (as opposed to captively produced and used hydrogen).

iii. Chemical Processes

Ammonia Synthesis Applications of Hydrogen Technologies

Methane has traditionally been the source of both hydrogen and process heat while ammonia synthesis from a methane feedstock has become a very well-understood, highly developed, highly efficient technology with little room for technological improvement.

Photochemical, Photoelectrochemical and -Photobiological Applications of Hydrogen Technologies

Some biological systems, though they require an additional absorption system because water molecules do not absorb radiation in the visible and near ultraviolet range, facilitate the direct photolysis of water. These systems include photochemical, photoelectrochemical, and photobiological processes. Photochemical water-splitting methods require a suitable absorber in which radiation is transformed initially into potential energy of an excited state, which in turn initiate subsequent processes that trigger chemical reactions by electron transfers
from an excited absorber system to a redox system. Photoelectrochemical water splitting is based on the absorption of photons and the generation of electron-hole pairs in a semiconductor in contact with an aqueous cycle.

In photobiological systems (still in an evolutionary stage) there exists in bacteria and blue algae prokaryotes and among some green algae eukaryotes the capability to release hydrogen and oxygen with the aid of solar energy. For example, in some green plants, as detailed in Winter and Nitsch, the conditions for photosynthesis can be altered such that the photosynthetic process will generate molecular hydrogen instead of reducing carbon. This process is induced by limiting the carbon dioxide available to the plant in addition to maintaining a very low oxygen level. The sensitivity of the enzyme system, which produces the molecular hydrogen, to the oxygen concentration appears to be a serious problem. A second example sourced from Penner, describes a blue-green alga which has been discovered to simultaneously produce molecular hydrogen and oxygen from water and light, although conversion efficiencies demonstrated so far for this and other systems capable of direct water photolysis are very low.

**Electrochemical Photolytic Applications of Hydrogen Technologies**

Semiconductor electrodes have been demonstrated to directly convert hydrogen via the photolysis of water in a four part process. The largely experimental work presented in Penner (p. 165) is of practical importance since it suggests that semiconducting materials can be found which will allow water photolysis with that portion of the solar spectrum having wavelengths shorter that about 10.4 Å (Angstrom). Water reacts with the semiconductor electrode to produce hydronium ions and gaseous oxygen, so that the electrons pass through the external circuit (in the direction opposite to the current direction) and then produce hydrogen at the platinum-black electrode to which the hydronium ions have moved.

**Cryogenic Applications of Hydrogen Technologies**

Some of the diverse potential uses of cryogenic liquids are refrigeration, freeze drying of foods, embrittlement of materials to enhance fracturing as a prelude to separation and recycling, and recycling of engine boil-off from liquid hydrogen used as a coolant which could be trapped and then consumed as a fuel by the user.
III. Rate of Development of Hydrogen as an Energy Source

III. Part A

The Dynamics of Hydrogen Technologies in the Marketplace

"The town gas networks of our parents' generation contained up to 60% $\text{H}_2$; an early B-57 in the late 1950s flew using hydrogen tanks pressurized with helium; field tests with automobiles have been undertaken in Germany and in the United States. Hydrogen is irreplaceable in coal liquefaction plants and for space flight; a 200-km gaseous hydrogen pipeline network has been in use in the German Ruhr area for several decades without accident; and the world's longest liquid hydrogen/liquid oxygen pipeline of 500 meters supplies the fuel tanks of the U.S. Space Transportation System at Cape Kennedy. " 13

i. The Role of Government

The unattractiveness of hydrogen in military applications, in light of the historical precedent which has witnessed military needs stimulate technological development and subsequent commercial application of technologies in many industrial sectors, has been limited in its promotion of the evolution of a hydrogen-based economy. The bulkiness of hydrogen fuel storage is incongruous with the military's need for small, sleek, highly, maneuverable, supersonic fighter aircraft and inconspicuous land vehicles, such as tanks. In addition, the extra procedures and precautions needed to liquefy and handle vast quantities of cryogenic hydrogen are not very compatible with combat. As a result of the government's space programs, fuel cells have been developed which have succeeded in increasingly efficient (between 50% and 60%) hydrogen/oxygen cells.

ii. Hydrogen-based Technologies

Hydrogen's clean combustion could warrant a price premium for hydrogen above alternative fuels because the expense of pollution control devices is largely avoided (although some control of nitrogen oxide might still be required).

Chemical Process Applications

Hydrogen has many applications as a chemical because it is an excellent reducing agent. (Chemical reduction is essentially the inverse of oxidation.) In many reducing applications, hydrogen is used to remove oxygen from a compound - for example, it is used to transform an oxide or sulfide metal ore into a raw metal, such as reducing iron oxide into iron and oxygen compounds, yielding iron. It is essential in reforming hydrocarbons (such as making plastics from oil), and it is necessary for synthesizing other chemicals, such as ammonia. Although not expected to play a significant role in developing a hydrogen-based economy, hydrogen is used in minor chemical applications in the food industry to transform unsaturated fats to saturated fats in, for example, the margarine, peanut butter and shortening industries. A new product, cellulosics, developed by the US Department of Agriculture (USDA) "could create a new American industry. Created by treating such non-woody agricultural wastes as wheat straw and corn stalks with hydrogen peroxide under alkaline conditions, the new product is a noncaloric substitute for flour and a natural source of dietary fiber. In animals that can break down cellulose, the same product provides a carbohydrate source; it also can be used in ethanol production." 14

Ammonia Synthesis Applications

Ammonia is one of the most basic chemicals used in modern industrial society. It is used as a feedstock for many chemical processes, as well as, for fertilizer - either directly or transformed into ammonium sulfate, nitrate, or urea. Although ammonia production has increased significantly in the 1970s, its future supply will largely depend on the degree of agricultural land in cultivation and the optimum bounds of fertilizer application rates. Production of essentially all ammonia in the United States is concentrated in an area around the Gulf of Mexico coast and the Southwest and is accomplished by synthesis from a nitrogen-hydrogen gas mixture derived from air and methane. Although there is no technological reason why new ammonia plants could not be designed to use a pure hydrogen feedstock, Dickson et al suggest that the assumption that ammonia will provide a large market for hydrogen in the future is overstated. One example they provide reasons that because the designs of present ammonia producing plants have been so highly integrated, abandonment of methane as an ammonia feedstock (due, for example, to developed cost advantages of hydrogen) would necessitate redesign of nearly the entire plant.

Cryogenic Applications

If additional and useful new materials are found that will superconduct in liquid hydrogen, important new uses for this hydrogen technology, as well as, synergisms with other aspects of the hydrogen economy will be

14 A Cellulose Filler for Calorie Counters, Spalding, B., chemical Week Vol: 140 Iss: 7, Feb 25, 1987, p. 34
established. For example, there is widespread expectation that materials will be found with transitional
temperatures higher than the 20.4 °K of liquid helium, thereby opening the way to use the cheaper more easily
liquified liquid hydrogen as a coolant in its place.

iii. Energy Utility Technologies

Gas Utility Applications

For residence and commercial applications, hydrogen can replace natural gas for its use in space heating by
combustion in conventional furnaces, space cooling by combustion in absorption-type conditioners, clothes-
drying appliances, stove-top and oven cooking, and hot water heating. In addition, already developed hydrogen
technologies would contribute new commercial applications such as cooking and heating by means of flameless
catalytic burners and (in-house) electricity production by means of a fuel cell.

Industrial use of hydrogen would go beyond the uses mentioned for residential and commercial applications to
combustion"for process heat and generation of process steam - processes which presently consume ca. 30% and
45% of U.S. industrial energy needs", respectively. When hydrogen is burned with pure oxygen to generate
process heat it is feasible to generate high-quality, high-purity steam directly, without the use of conventional
boilers. There are considerable advantages to producing steam in this manner; the steam is produced at a very
high temperature, the steam is very pure, and since not even nitrogen oxide is produced and the sole combustion
product is steam, there is no need to provide controls for air pollutants.

ii. Electric Utility Technologies

The potential applications of hydrogen technologies for the production of electricity are a function of the
diversity of the alternative electricity-generating technologies. Consequently a brief discussion of technological
developments in the nuclear, solar, hydroelectric energy technology fields are presented.

Nuclear Energy - Hydrogen Technology Applications

As a hydrogen production process, nuclear energy generates electricity, which is then employed in the
electrolysis of water, or heat. Nuclear reactor technologies include light water, fast breeder and helium cooled

15The Hydrogen Energy Economy: A Realistic Appraisal of Prospects and Impacts, Dickson, E., Praeger
Publishers, NY, 1977, p. 75
high-temperature designs. While nuclear fusion still has to prove its technical feasibility, nuclear fission has been used commercially to produce power since about 1960. (Please see Appendix 13)

While commercial use of breeder reactors would permit a much better utilization of existing uranium reserves, its reactor technology is substantially complex and controversial - which explains why commercial application has been restricted almost entirely to conventional light water reactors. Light water reactors have been built in two versions - pressurized, in which water (at a pressure of about 150 bar) acts as a circulating heat-carrying medium employing a primary and secondary loop; and boiling water (operating at 70 bar pressure) in which a heat exchanger is not needed - thereby eliminating turbine contamination. In both forms of light water reactor, average temperature levels of 300 °C make possible the generation of power plus the utilization of low-temperature heat. Fast breeder reactor prototypes have been built in Great Britain, France, the Federal Republic of Germany and the Soviet Union. In addition to power generation, the helium cooled high-temperature reactor can produce heat that can be used in various endothermic processes such as coal gasification, tow gas methanization, methane splitting and thermochemical water splitting. A single prototype has been built in Hamm-Uentrop (FRG). 16

Solar Energy - Hydrogen Technology Applications

Energy-conversion efficiencies are very low for solar generated energy so that it represents an unusual challenge for engineers to design and fabricate material-efficient solar energy utilization technologies that at the same time offer good energy conversion efficiencies. Conversion of solar energy to electricity may be accomplished by employing a Rankine-cycle engine, in conjunction with a turbine generator, and by using existing thermal gradients in the oceans whereby hydrogen is in turn manufactured by electrolysis. Solar-thermal hydrogen energy conversion, or the conversion of radiation energy into heat, is currently the best known and most expensive method of using solar energy. The exploitation of ocean thermal gradients, solar-sea generation of hydrogen, to generate energy is only feasible if the energy can be transported to shore in the form of hydrogen.

The key components in solar plant design are temperature level and proportion of usable energy, which are determined to a great extent by the absorber surface characteristics and the radiation concentration. The optical limits for solar radiation concentration are determined by the apparent size of the solar disk. The solar tower seems to be both technically and economically the most promising concept for large solar plants (minimum of 50 Mw). Winter and Nitsch (p. 41) describe the operation of a solar tower as numerous sun-tracking mirrors (heliostats) concentrate the sun's radiation on a receiver at the top of a tower. This absorbs and transfers about

80 to 90% of the incoming radiation to a heat-carrying medium (water, air, salt, sodium). High-temperature heat can be generated at an average annual efficiency of 50%.

An alternative to solar tower technology is parabolic concentrator technology which describes a system composed of rigid reflectors, membrane reflectors or mirrors and systems with secondary reflectors which combine to represent the most effective utilization of direct solar radiation. Parabolic concentrator collector technologies as described by Winter and Nitsch have demonstrated efficiencies of more than 80%, translating into annual conversion efficiencies of 70 to 75%. However, because parabolic dishes are stand alone units, there are losses associated with bringing together the decentralized heat sources. As a result, dish technology is suitable only to service process heat plants (max 10 Mw) for decentralized uses and small consumers - coupled, for example, with a thermal power engine to generate electricity.

iv. Transportation Fuel Technologies

Automotive Applications

The key technologies complementing hydrogen use in automobiles are cryogenic liquids handling and storage, lightweight low-cost metal hydrides using abundant materials, and engine alloy that resist hydrogen environment embrittlement. With relatively minor and simple adaptations engines run well and cleanly on hydrogen and air (even more cleanly on pure hydrogen and oxygen because nitrogen oxide cannot form). The ease of adapting stock engines has brought much attention to the clean air advantages of hydrogen fuel in place of gasoline or other chemicals containing carbon. In addition, some claims have been made that hydrogen increases the efficiency of internal combustion engines. The clean air advantage of hydrogen-fueled engines should remain even if external combustion engines displace the internal combustion engine.

Aircraft Applications

The storage volume required for fuel storage is not significantly larger in a hydrogen-fueled airplane than in a conventional jet which led to the conclusion in a Lockheed study that from safety, structural and effectiveness points of view that only a minor engineering change - a relocation of the fuel tanks inside the fuselage in front of and behind the passenger cabin - would be required to transfer to hydrogen-fueled aircraft. 17

v. Alternatives to Hydrogen Energy Technologies

i. Non-Hydrogen Chemical Process Applications

Processes that indirectly convert methane into more transportable products, such as methanol and ammonia, begin with the capital-intensive steam reforming of methane into synthesis gas - a mixture of carbon monoxide and hydrogen. Numerous research projects are now underway to eliminate the need for steam reforming. Attention is being focussed on the commercial applications of new superconductivity technologies, the results of which would generally promote the liquid nitrogen industry.

ii. Non-Hydrogen Energy Utilities Applications

Gas Utility Applications

The natural gas industry is turning not to hydrogen technologies but to coal gasification to produce synthetic methane. Natural gas has been preferred to hydrogen by industry because of its (artificially) low cost and very clean combustion properties (which lower cost of pollution control). During the 1970s, reserves of methane had been falling from a combination of soaring demand and disincentives for companies to explore as a result of price regulation (ceilings) imposed by the U.S. Federal Power Commission. Methane, the major component of natural gas, is a relatively clean-burning fuel, and it is easy to control, store and distribute. Although coal gasification would cease to be a cheap source of methane as increased demand for coal raised its price, it is at present preferred to hydrogen for a variety of reasons, including the facts that if can be blended with natural gas supplied with no change being apparent to the customer and no change being required in gas utility distribution networks.

Electric Utility Applications

While building facilities to meet increasing electricity demands, electric utilities have, at the same time, shown interest in more efficiently meeting significant variations in demand - at different times of the day, different days of the week, and different months of the year. Alternatives have included institutional mechanisms (such as variable pricing) that would tend to smooth demand as well as several forms of energy storage, which allows base-load facilities to meet some of the intermediate-load demand. Hydrogen (best matched to nuclear or solar

power because it provides a means of converting the otherwise unstorable heat output of a reactor into a storable fuel) can be produced with off-peak power, stored, and then later consumed to generate peak power, thereby serving as a cheap chemical analogue to pumped hydroelectric storage.

Utilities categorize their load profiles into base, intermediate, and peak components. They allocate their most efficient and reliable generating equipment (nuclear reactors and the best fossil-fuel-fired plants), typically their newest and most expensive, to base-load service. Nuclear reactors, for example, are so employed because they have higher (per unit output) investment costs and because they have difficulty varying their output to swings in demand; and because they are most productively used on a constant basis, operating at their full rated capacity. The older, less reliable, and less efficient fossil-fired plants are used for intermediate-load service, while peak-load power is often supplied by inefficient turbine generators that are costly to operate. When available, hydroelectric power is devoted to intermediate- or peak-load applications - except in regions with abundant hydroelectric power, where contributes to base load demand.

Water Electrolysis

Currently existing electrolytic plants manufacturing hydrogen "operate at overall efficiencies of 60 to 100% and are only a factor of ten smaller than the commercial electrolysis units which will be required for large-scale implementation of hydrogen manufacture in a hydrogen economy." Penner proposes that the prospects for water electrolysis will improve only under conditions that do not exist so far but are expected to arise in the future: his examples include the pressure to reduce CO₂ emissions, the opening up of unusually cheap hydro-power energy reserves, such as in Greenland, the construction of new, large nuclear electric power plants as well as the prospect of linking photovoltaic plants in distant regions with additional electrolytic hydrogen factories.

iii. Non-Hydrogen Thermochemical Production Technologies

Actual evaluation of thermochemical production requires detailed knowledge of chemical kinetics, a subject in which good experimental information is difficult to obtain and in which reliable theoretical estimates cannot be performed. It will, therefore, require years of difficult experimental work to determine a number of preferred thermochemical cycle processes for the production of hydrogen. Thermionic devices have been widely used only in laboratory studies. Penner gives an example of a type of high-pressure converter that has been developed to deliver ca. 40 cm² for emitter temperatures of 2,200 °K with overall efficiencies of 20%. The point out that

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although central-station power applications of these devices has not been considered because of prohibitive costs, (undersea) thermionic devices have been proposed as elements of a power reactor for nuclear-energy sources.

**Fuel Cell Applications**

The history of hydrogen fuel cell technology began in the 19th century. Winter and Nitsch (pp. 40-41) trace the earliest experiments involving electrochemical processes to have been conducted in England in 1839 (Grove) and later in 1880 (Westphal) and 1984 (Oswald) where it was demonstrated that almost all chemical energy can be converted to electrical energy in the hydrogen/air reaction. The fuel cell application of hydrogen suggests that if hydrogen were widely distributed to residences, an "all-hydrogen home" analogous to an "all-electric home" would be possible, although this would mean that the size of the fuel cell would have to be chosen to meet peak demands unless some kind of off-peak electric storage device, such as a battery, were used. Aside from the necessary increase in both the durability and dependability of fuel cells, further development is expected to decrease the cost of electrode materials and to simplify production methods.

iv. **Non-Hydrogen Transportation Fuel Technologies**

Hydrogen's demonstrated suitability for combustion in nearly every class of engine implies that there should be no major technological barriers to its use in either automotive, aeronautic, nautical or train transportation vehicles. At the same time, however, there exist many competitive alternative fuel technologies to hydrogen - in particular, synthetic crude oils and ethyl alcohols, especially attractive because they are renewable energy sources and complement the agricultural sector.

**Automotive Applications**

The leading automotive technological alternatives to hydrogen are diverse. They include fuels - synthetic gasoline and diesel, methanol, gasoline/methanol blends, propane, liquid methane, and hydrogen; electric vehicles - battery, flywheel and fuel cell; and engines - gas turbines, external combustion, rotary and modified reciprocating, such as stratified charge. In their attempt to forestall mandatory use of cleaner-burning fuels such as methanol, oil companies such as ARCO and Shell have introduced reformulated gasolines in major US cities. A recent study suggests that "most manufacturers see a future in different engine types running on different fuels, often multiple fuels in the same engine, depending on conditions. Almost inevitably, gasoline will come first, supplemented by liquid petroleum gas or alcohol."

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21 Race for a Clean Machine, Laban, B., Business, Sep 1990, p. 34
iv. **Research and Development Priorities**

A first priority toward the advancement of the hydrogen based economy would need to be placed on the development of advanced concept hydrogen coproduction technologies, especially high-pressure, high-temperature electrolysis and closed-cycle thermochemical processes. Dickson et al theorize that without considerable cost reductions in coproduction technologies, all other questions about hydrogen are not viable. The following government agencies, as well as, by participants in the industry have sponsored hydrogen technologies since at least the early 1970s - examples include, the Department of Energy, Department of Transportation, Department of Defense, NASA, and the Environmental Protection Agency.

Technologies that complement hydrogen used as an energy carrier and which, therefore, should receive attention for development funding are any that are either themselves made more effective by the use of hydrogen or those that make the use of hydrogen cheaper or more convenient. These technologies include "simpler and cheaper cryogenic liquid production, storage, and distribution, steels immune to hydrogen environment embrittlement, lightweight metal hydrides composed only of abundant materials, low-cost, high-efficiency catalysts for electrolyzers and fuel cells using only abundant materials, and corrosion-resistant metal alloys suitable for high-temperature thermochemical water-splitting containment." 22 Conservation and cogeneration technologies such as heat pumps, waste heat utilization and thermal insulation, will be indispensable in a hydrogen economy.

i. **Chemical Processes**

In the event that superconductors with higher transition temperatures (the temperature at which material undergoes a transition from a normal, resistive conductor to a superconducting, resistanceless material) are found, liquid hydrogen might serve as the cryogenic coolant instead of the more expensive and more scarce liquid helium. 23 Flameless catalytic combustion of hydrogen is a reasonably well-developed technology - temperatures can be varied between those low enough for mere warmth and high enough for cooking. Despite government funding setbacks, the US is increasing its participation in solar chemical processing activities, such as solar detoxification, a process which destroy dioxins. For example, "the Sandia National Laboratories is working with the Germans on a process in which methane and carbon dioxide are converted into hydrogen and carbon monoxide." 24

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24 A New Direction for Solar Energy, Parkinson, g., Chemical Week vol: 142 Iss: 25, Jun 22, 1988, p. 10
Fuel Cell Applications

Active research has been underway for some years to develop high-temperature fuel cells operating near 1,000 °K with overall efficiencies of about 60%, although realization of cells of this type is considered years away. During the 1970s, fuel cell development was supported by 35 natural-gas transmission companies under the TARGET (Team to Advance Research for Gas Energy Transformation) program. Dickson et al. point out that as early as 1972 ca. 60 fuel-cell stations were being tested at 37 locations in the US and Canada. 25

ii. Hydrogen Production Technologies

Experimentation with production techniques is naturally predicated on the concurrent development of advanced materials suitable for containing the high-temperature, corrosive chemicals to be used in closed-cycle thermochemical processes. Winter and Nitsch (p.1) point out that engineers working in energy economics, in the chemical industry and in cryotechnology are particularly relevant for development in the storage and transport of gaseous or liquid energy carriers. They also cite solid state physicists and materials scientists who are working on the brittleness of materials and storability in metal hydrides - both a positive and a negative aspect of the very specific tendency of hydrogen to diffuse in materials.

In light of inevitable environmental trends (i.e., re leakage, spillage etc.,) research should focus on the investigation under realistic conditions (temperature, pressure, and hydrogen purity) of hydrogen-environment embrittlement in materials expected to be used in a hydrogen economy. A corresponding emphasis should be placed on analyzing hydrogen safety in realistic environments and under realistic operational conditions. On a grander longer-term scale, priority should be set for undertaking systems modeling of the U.S. energy economy to produce scenarios of hydrogen cost, interfuel competition price relationships, environmental protection, and institutional constraints.

iii. Hydrogen Fuel Storage Technologies

Hydrogen is distinctly more dangerous in moving from deflagrations to detonations because of its higher burning velocity. However, advances have been made in understanding the complex processes in the deflagration and detonation of combustible gases in the past few years, a trend which is likely to continue. The development of hydrogen energy storage systems for use by electrical utilities for load-leveling applications, already in use in Europe, would further complement the adoption of hydrogen for this application.

iv. **Hydrogen Fuel Transportation Technologies**

Advanced-design turbine-powered trains are under development both in this country and abroad, although the effort has until recently received only modest funding. Dickson et al (p. 93) mention that it has been demonstrated (with models) that magnetic levitation using superconducting electromagnets, cooled by liquid helium is technically feasible for a train running on special guideways. A magnetic levitation train could conceivably utilize hydrogen both as a coolant and then as a fuel - similar to its use in hypersonic aircraft.

v. **The International Development of Hydrogen-based Energy Systems**

There exists dramatic potential in non-Industrialized but sun-rich countries to restructure the balance of world energy supplies - for example, by encouraging the potential of decentralized solar energy plants employing hydrogen as an energy storage medium. Solar energy could conceivably initiate the gradual elimination of the North-South differential between developing and developed countries; the degree of their mutual dependence would be lessened because would be distributed over several countries and because the number and total acreage of future solar and nuclear hydrogen production sites would far outnumber the world's oil and gas production sites. An interesting perspective is gained by introducing the fact that " a total of 28,000 km$^2$, equal to only 0.3% of the Sahara's surface, are needed to produce the solar hydrogen equivalent to the entire energy demand (260 million tce/a) of Europe's largest industrial country, the Federal Republic of Germany." 26

Solar power plants will be located only in sunny parts of the world (between 30 to 40° N/S) where both the amount of concentratable solar energy and the numbers of hours of sunshine are two to three times higher than in the industrialized energy user zones of the world's northern hemisphere. Regions best suited geographically for large-scale solar plants, largely located in Third World land areas, are flat surfaces without vegetation, without valleys or mountains and with solid ground, little wind and little rainfall. In addition, a plant location's man-made features must be considered, such as present use and transportation access. Gravel and stone deserts such as those that occur on large scale in North Africa, on the Arabian Peninsula, in Australia and less often in Iran are most suitable. As Winter and Nitsch point out (p.132), the present production rate for solar cells is about 30-40 MW tce/a (1987) and has almost doubled annually from 1978 to 1984.

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III. Part B

A Time-Series Analysis of Hydrogen-based Research

i. Introduction

Evidence researched by Winter and Nitsch identify the propensity of an anti-cyclically oriented volume of scientific publication which persists in stable economic times for more critical future periods. There is also evidence that any significant contribution by a new energy carrier of ca., 10% to the national energy supply of an industrialized country has always been preceded by an introductory phase, typically several decades. This was so, for example, two centuries ago with coal and in more recent times with oil, and it applies equally to nuclear and hydroelectric energy now. The nuclear energy industry was initiated in the 1950s and today constitutes barely 12% of this country's total consumption.

ii. Time-Series Analysis: Numbers of Articles versus Years 1900 - 1990

A comparison of the number of articles published (including patents, technical reports and conference findings) in reference to hydrogen-based technologies during the twentieth century demonstrates a dramatically increasing trend, signifying the increasing importance placed on the field by governments and industry alike. (Please see Graph I, Hydrogen-based Research # Published Data, Years: 1900 - 1990)

Graph I:

Hydrogen-based Research -# Published Data
Years: 1900 - 1990

Source: Dialog Information Services, U.S. Department of Energy, Energy Science and Technology, Files 103-104
Data Search: Hydrogen Fuels, Hydrogen Technology
iii. Time Series Analysis: Hydrogen Research Sites versus Years 1900 - 1990

An analysis of the world-wide distribution of published articles on hydrogen-based technologies demonstrates that the industrialized countries - in particular, the United States, Japan and Germany - account for the majority of activity. The dramatic increase of activity demonstrated in Graph I during the 1970s is assumedly a reflection of the instability during that time of world oil prices, reflecting the vulnerability of supply channels - a factor which has in the past and will undoubtedly, in the future, be a primary motivation in continued research in both hydrogen and alternative energy technologies. (Please see Graph II, Hydrogen-based Research World Regional Distribution, Years: 1970 - 1990)

Graph II:

Hydrogen-based Research World Regional Distribution
Years: 1970 - 1990

Note: Western Europe includes both EEC and non-EEC, but not formerly Eastern Block member countries
Source: NTIS and Compendex Information Services, Barker Library Data Files, Massachusetts Institute of Technology
iv. **Time Series Analysis: Individuals versus Years**

An analysis of the distribution of researchers most active in hydrogen-based technologies in government, universities and industry is relevant in that it demonstrates a substantially widely distributed participation in the field. (Please see [Graph III, World-Wide Distribution of Most Active Hydrogen Technology Researchers, 1970 - 1990](#))

**Graph III:**

**World-Wide Distribution of Most Active Hydrogen Technology Researchers, 1970 - 1990**

![Graph III](image)

**Individual Publishing Researchers**

**Note:**

i E. Greenbaum, Oak Ridge National Laboratory, TN, 1986 - 1990;  
ii A.J. Frank, Solar Energy Research Institute, CO, 1984 - 1988;  
iii N.G. Eror, Oregon Graduate Center, OR, 1984 - 1986;  
v L. Kohout, NASA, OH, 1986 - 1989;  
vii A.J. Bard, Texas University, Austin TX, 1985 - 1987;  
ix M. Steinberg, Brookhaven National Lab, NY, 1984 - 1989;  
x B. Vigeholm, Risoe National Laboratory, Denmark, 1989;  
xxi J.M. Toepfer, Daimler-Benz AG., Germany, 1979 - 1983;  
xxii T. Kanda, National Aerospace Laboratory, Japan, NA;  
xxiv P.M. Vignais, Commission of the European Communities, Luxembourg, 1984 - 1986;  
xxv D.G. Ivey, University of Windsor, Ontario CN, 1986 - 1988;  
xxvi K. F. Knoche, RWTH, Germany, 1982 - 1988;  
xxvii P.A. Kramer, Messerschmidt-Boelkow-Blohm GmbH, Germany, NA;  
xxviii A. Chikdane, Centre d'Etudes Nucleaires de Grenoble, France, 1988 - 1989;  
xxix G.N. Voloshchenko, Mosco Power Engineering Institute, USSR, NA;  
xx V.V. Shokorod, Academy of Sciences of the Ukranian SSR, USSR, NA

**Source:** NTIS and Compendex Information Services, Barker Library Data Files, Massachusetts Institute of Technology


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iv. **Time-Series Analysis: Distribution of Institutions Active in Hydrogen-based Research**

Analysis of the distribution of individuals involved in hydrogen-based technology research confirms the findings of the preceding graphs. While there is a heavy concentration in the industrialized countries, not insignificant evidence suggests that involvement in the field is continuing to increase on a world-side scale - to include, for example, the Eastern Block countries, India, Pakistan, Finland and Sweden. (Please see Graph IV, World-Wide Distribution of Institutions Most Active in Hydrogen-based Research, 1970 - 1990)

**Graph IV:**

**World-Wide Distribution of Institutions Most Active in Hydrogen-based Research, 1970 - 1990**

![Graph Image]

**Government Agencies, Universities, and Industry**

**Note:**

i National Aeronautics and Space Administration (NASA), OH, VA Wash. D.C., MD, USA;

ii Brookhaven National Lab, NY, USA;

iii Commission of the European Communities, Luxembourg;

iv Technische Hochschule (RWTH), Aachen, Germany;

v Solar Energy Research Institute, Golden, CO, USA;

vi Department of Energy, Oak Ridge National Laboratory, Technology Div., TN, USA;

vii North Dakota University, Energy Research Center, Grand Forks, ND;

viii Oak Ridge National Lab, Chemical Technology Div., TN, USA;

ix Los Alamos National Lab, Applied Th. Physics Div, Los Alamos, NM, USA;

x Texas A & M University, Hydrogen Research Center, College Station, TX, USA;

xi Bundesministerium fuer Forschung und Technologie, Bonn, Germany;

xii Lawrence Berkeley Lab, Materials & Molecular Research Div, Berkeley, Ca, USA;

xiii Agency of Industrial Science and Technology, Tokyo, Japan;

xiv Institute fuer Technische Physik (DFVLR), Stuttgart, Germany;

xv Centre d'Etudes Nucleaires de Grenoble, France;

xvi Tokyo Institute of Technology, Dep of chemical Engineering, Tokyo, Japan;

xvii Exxon Research and Engineering Co, Annandale, NJ, USA;

xviii I. V. Kurchatov Inst. of Atomic Energy, Moscow, USSR;

xix Westinghouse Electric Corporation, Advanced Energy Systems Div., Pittsburgh, PA, USA;

xx Academy of Sciences of the USSR, Ural Science Center, USSR

**Source:** NTIS and Compendex Information Services, Barker Library Data Files, MIT, Cambridge, MA

"The use of fossil fuel energy carriers is sharply reduced, and petroleum and natural gas have been largely replaced. Coal is used for electricity and district-heat generation. Non-fossil fuel generated hydrogen meets end user energy demands together with electricity, district heat and solar energy in the form of radiation energy, ambient heat and biomass. Petroleum or synthetic hydrocarbons are available for transportation and non-energetic use. Hydrogen is brought into the energy system in a manner similar to natural gas today - mainly as imported energy carrier pipelines or tankers, and, to a smaller extent, produced from off-peak power to ensure high utilization." 27

IV. **The Rate of Adoption of Hydrogen-based Energy Technologies**

i. **The Hydrogen Economy**

In the hydrogen economy, the energy networks will be integrated such that the established electricity grid and a new hydrogen grid, based on natural gas pipeline systems, will be linked to each other via electrolysis and fuel cells. Winter and Nitsch suggest that "electricity utilities will turn into "energy utilities" power plants will turn into "energy plants" in that they will supply not only electricity and district heat, but also electricity, district and chemical-process heat in the form of gaseous and liquid hydrogen." 28 Those regions of the earth (many central European countries and Japan) which have neither sufficiently high insolation to operate large solar plants nor the necessary locations of large nuclear hydrogen plants will, however, most likely retain their dependence on imported energy carriers even in a hydrogen economy. (Please see Appendices 14 - 15)

Total hydrogen potential today amounts to 2,300 million tce/year - a figure which Winter and Nitsch (p. 300) propose could be expected to stabilize at approximately 5,000 million tce/year by 2030 or roughly 45% of energy consumption. At the same time, estimates of the future utilization of hydrogen technologies vary dramatically. The use of hydrogen might account for a maximum market share between 20 and 30% of total fuel consumption if one sees fuel for public and freight transportation as the focal point of hydrogen use. The transportation sector is, however, likely to be covered by liquid hydrocarbons in the long term, since its higher volume-specific energy content and unproblematic storage predestine it for continued dominance in commercial and recreational transportation uses. If one considers possibilities for using non-fossil hydrogen in chemical processes, for example, the direct reduction of iron and in coal upgrading, or limited to the manufacture of synthetic fuels, hydrogen's then total share of final energy consumption could reach 40 to 50% in the hydrogen economy.

ii. **The Rate of Adoption of Hydrogen-based Technologies**

The Rate of Adoption of Hydrogen-based Technologies will vary dramatically between small and large-scale application. For example, while hydrogen's adoption as a substitute for gasoline-fueled automobiles is unlikely to occur in the near future - if ever, its imminent adoption as an energy carrier of choice in solar fuel cell technology appears very likely.

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Electrolysis

The production of hydrogen by electrolysis of water has long been commercially feasible. In fact, electrolytic hydrogen plants have been operating since the 1940s - the largest is at Rjakon, Norway with a capacity of 284,600 lbs of hydrogen production per day. An experimental solar hydrogen power station has been established at Neunburg vorm Wald, using solar energy to power two electrolysis plants, the combined output of which is 210 kW. The long-term economic feasibility of electrolysis will depend on low capital costs, high efficiency and, most important, the cost of electricity. Dickson et al suggest that the production cost of hydrogen would benefit from sales of (by-product) oxygen - in those cases where a demand exists as a necessary incentive to compensate for then currently prohibitively expensive costs of manufacture. 29 (Please see Appendix 16)

Thermochemical Processes

Thermochemical decomposition is expected to have an economic advantage over the electrolytic production process because the intermediate step of converting nuclear heat to electrical energy is eliminated, thereby reducing the need for expensive generating equipment and, at the same time, eliminating the conversion energy losses. The use of nuclear heat as a source of energy for the thermochemical decomposition of water is an attractive prospective technology for the production of hydrogen because it offers potentially superior energy efficiency. The eventual cost of thermochemical hydrogen depends primarily on the cost of the nuclear heat source and the cost of thermochemical conversion processes; the latter is especially uncertain at this time. It is, of course, difficult to determine cost estimates for nuclear-produced heat from published costs of nuclear-produced electricity because estimates for nuclear power installations include extended interest charges, electrical generation equipment, the cost of funds invested during construction and cost escalation of equipment, materials, and labor.

The Role of Industrialized and non-Industrialized Countries

The industrialized countries, possible supported by sun-rich, at present oil-exporting countries, should be the initiators of a long-term technology transfer which would contribute to the development of an energy infrastructure for developing countries, with special emphasis on solar technology. Hydrogen production is even more closely tied to solar energy in the developing countries than is the case in industrialized countries, although coal beds deposits in the industrializing countries of eastern Europe would contradict this observation.

for that region of the lesser developed world. Most sun-rich countries are concentrated in North Africa and the Arabian Peninsula. These regions account for 90% of the areas worldwide in which insolation achieves at least 90% of the maximum radiation amount possible. In terms of global perspective, the sun-rich regions of North and South America are less important.

Solar technologies for rural areas need storage systems to meet energy demand - his the only way they can compete with the currently widespread diesel generators in producing power. Hydrogen manufactured by decentralized solar cell plants could take over the fuel supply and meet the heating and electricity demands of numerous remote villages. Hydrogen production and consumption might produce as much as one-third of the energy consumption in these countries.

i. Chemical Process Technologies

A major dislocation in ammonia supplies (vis-a-vis dwindling natural gas and methane supplies) would be dramatic ramifications for the food supply, food prices, and the U.S. balance of trade. There exists the possibility that ammonia producers, therefore, might produce strong incentive to eventual hydrogen-based technologies in as far as their product is crucial to agriculture. In addition, because of the clean combustion properties of hydrogen, industries would find special advantage in its combustion for process heat. Another emerging process "uses excess hydrogen and catalysts to convert contaminants in waste hydrocarbon liquors."

ii. Energy Utilities Technologies

Gas Utility Applications

The primary product of hydrogen combustion is water vapor so that hydrogen offers an advantage over methane combustion for space heating because venting would not be necessary to exhaust toxic combustion products (especially carbon monoxide). Although both methane and hydrogen systems require air infiltration to provide the oxygen to support combustion, the hydrogen system eliminates the need for an exhaust system, saving the loss of heat up the flue and thereby yielding a more efficiency (cheaper) commercial and residential heating system. Moreover, in cold winter climates the buildup of humidity (appropriately controlled) would increase human comfort in the normally dry, heated indoor air.

\[^30\] New Options Take on Incineration, Chynoweth, E., Chemical Week Vol: 147 Iss: 7, Aug 22, 1990, p. 49
Electric Utility Applications

Nuclear power, hydroelectric, solar energy, and coal are the four key energy sources for producing hydrogen in conjunction with electricity applications.

The Role of Hydropower Energy

With the exception of a few large plants, the world's hydroelectric plant energy is not used to produce hydrogen. While an average of only 8% of world hydropower potential is being utilized, the future growth of this energy technology is more likely will to be used to cover the large industrial and private demand backlog for electrical energy - not for electrolytic hydrogen production. The largest proportion of the hydropower potential of the OECD countries exists in the USA (Alaska) and Canada (Quebec, Newfoundland) where utilization could increase from today's 42% to 75% by the year 2030. Other OECD nations utilize already up to about 60% of the hydropower and this could reach 80% by the year 2030 - about 30% of which could be employed for electrolytic hydrogen production. It is estimated that today's annual production of hydroelectric energy 1,700 TWh/a will increase to 3,900 TWh/a by the year 2030.\textsuperscript{31} evidence that hydroelectrically produced hydrogen can only play a supplemental role in meeting energy demand in the future.

The Role of Nuclear-Powered Energy

Without nuclear power the hydrogen economy concept would rely on coal gasification in the short run and solar or hydropower in the long run, so that probably the single most critical factor in the long-term viability of a hydrogen economy is the fate of nuclear power. The costs of a nuclear power plant represent a significant initial barrier to increased introduction largely because of significant capital costs complicated by price increases and interest expenses incurred in the nine years it takes to have one built. In addition there are not insignificant environmental aspects of a nuclear-fueled hydrogen economy which essentially translates into the negative environmental aspects of nuclear power - discharge of heat into the air or water (depending on the approach to cooling), low-level release of radionuclides during normal plant operation, and potential accidental release of large amounts of radionuclides during fuel reprocessing and waste disposal. An estimate of the number of nuclear electrolysis plants needed to supply a hydrogen economy would include 40 plants for the aviation sector, 340 for residential heating supply, and 270 for transportation fuels (1 GW electric = 0.53 GW H\textsubscript{2}).\textsuperscript{32} (Please see Appendix 17 - 18)

\textsuperscript{32} Hydrogen, Master-Key to the Energy Market, Marchetti, Eurospectra 9, 1970, p. 35
The Role of Solar-Powered Energy

Many solar energy technologies require means to store energy before the energy becomes useful which would, in turn, stimulate delivery of energy in hydrogen form. Highly focused solar energy is another heat source that has been proposed for thermochemical decomposition. However, precision, steerable, focused solar collectors are so expensive that a solar-powered system is unlikely to be economically competitive with nuclear heat. Numerous decentralized solar energy use technologies which are not yet in economical today, are generally expected to be in abundance in the next century, especially in the energy supply structures of high-insolation countries.

The Role of Wind-Powered Energy

Wind energy is an unlimited energy source that will eventually compete economically with conventional energy technologies. There are only a few regions worldwide (Patagonia, Somalia and the southwestern coast of Australia) appropriate for large-area wind energy use. Wind-rich mainland regions consist almost entirely of narrow, populated strips of mountainous coastline, making wind power installations impractical there for economical and ecological reasons. Individual plants of 100 to 1,000 kw_e output will be the mainstays but large combined systems with a total output of 300 Mw_e are also being discussed. Instead of feeding energy into an existing grid, wind parks could produce (storable) hydrogen - an alternative which would alleviate the present inability of wind energy technologies to harness the substantial wind energy potential restricted to some of the earth's remote windy regions.

iii. Transportation Fuel Technologies

Because of the diversity of components in an engine, on-board storage and distribution to the vehicles requirements of the multifarious "transportation" vehicles (shipping, automobile, aircraft, heavy machinery) it is important to categorize individual sectors in terms of their performance with hydrogen-based fuel technologies. The use of hydrogen could be implemented far more easily in fleet vehicles, for example, than in either private automobiles or off-the-road vehicles such as earthmovers, farm machinery, mining machinery, snowmobiles, motorcycles, forklifts and so forth.

Automotive Applications

Large-sized engines generally show better thermal efficiency (because of a smaller surface to volume ratio in the combustion chamber) than small engines. Thus the trend toward smaller, lighter cars with smaller engines now begun in order to decrease automotive fuel consumption is likely to lessen the net effect of the improved
efficiency reported for hydrogen. On the other hand, the superinsulation systems presently employed in the
design of liquid natural gas and liquid petroleum gas ocean tankers can be transferred to future hydrogen tankers.
While a number of problems exist in connection with hydrogen's low density and the resulting larger storage
volume, a hydrogen-propulsion ship would realize improvements in efficiency, performance, weight and
volume. Use of hydrogen to fuel gas turbine trains would reduce air pollution and, possibly, engine noise.
Trains are not strongly constrained in their total volume, although they are severely limited in cross-section ( set
by the clearance dimensions of tunnels, bridges, parallel tracks, and so on ).

Aeronautic and Nautical Applications

The production of vast quantities of hydrogen and a large throughput in the logistics system to support a vast
commercial fleet of liquid hydrogen airplanes would be simplified by the need for relatively few distribution
points. This advantage is not as great in subsonic ( commercial ) aircraft. The top 25 airports in the country
handle about 76% of all air passengers, and the top 10 airports handle about 70% of all passengers, as few as 10
airports equipped to dispense hydrogen fuel would suffice to accommodate U.S. long-distance travel demands. A
( 1970 ) Lockheed study also showed that " an optimized liquid-hydrogen-fueled subsonic passenger plane would
posses the following attributes when compared with an advanced design airplane using conventional jet fuel: less
gross takeoff weight, nearly equal empty weight, lower emissions of air pollutants ( only nitrogen oxides ),
shorter takeoff distance ( about 3 - 5% reduction), less noise in the takeoff zone, slightly more noise in the
landing zone, slightly higher aircraft sales price ( about 3% ), and loser energy utilization per passenger mile. "
33

iv. Alternatives to Hydrogen Energy Technologies

Hydrogen has a higher price per unit energy than petroleum products largely because petroleum products are
naturally liquid at room temperatures and, consequently, more easily transported. Petroleum companies and the
fuel-supply sector in general have a strong incentive to develop and produce synthetic fuels essentially identical
to current petroleum products - this enables them to protect their very large investments in existing refining,
storage, and distribution facilities.

i. Non-Hydrogen Chemical Process Applications

33The Hydrogen Energy Economy: A Realistic Appraisal of Prospects and Impacts, Dickson, E., Praeger
Publishers, NY, 1977, p. 89
Only if hydrogen became available at a lower cost than it could be obtained from methane or alternative hydrocarbon fuels, is it probable that new ammonia plants would be prescribed to use lower-cost hydrogen feedstock - otherwise, nearly any alternative liquid or gaseous hydrocarbon would replace methane before hydrogen.

Iron Ore Reduction

Only hydrogen and carbon compounds can be made available in the large quantities needed as reducing agents while only hydrogen seems to be a viable alternative to conventional coking coal methods that does not depend on a fossil-fuel resource. Besides the coke presently used, charcoal from any source (such as wood-processing waste) or carbon monoxide might be used as alternative technologies to hydrogen.

ii. Non-Hydrogen Energy Utility Technologies

As a simple matter of efficiency, once energy was in the form of hydrogen, there would be an incentive to sell it directly rather than to pay the energy loss penalty of reconversion to electricity. As an alternative, not only is electricity a very high-quality and efficient form of energy; but, like hydrogen, it is environmentally clean, and electrical end-use devices are quiet.

Gas Utility Non-Hydrogen Applications

The largest use of gas in homes and commercial establishments is for space heating (about 20% for residence and about 65% for commercial). The natural gas industry's position on adopting hydrogen technologies will be preceded by developments in coal gasification, methane availability and the supply of natural gas reserves. The effect of improvements in process technologies is unclear. For example, modern electric "heat pumps", which can be used for cooling as well as heating and which can provide space heating at a cost and total energy efficiency nearly identical to that of conventional gas combustion heaters, can be adopted by both hydrogen-fueled and natural gas-fueled facilities.

Electric Utility Non-Hydrogen Applications

Significant innovation in the electric power sector would greatly undermine the future role of hydrogen delivered to homes and commercial industry. Electricity, like the petroleum industry, shares obvious structural advantages over hydrogen in addition to being able to source a variety of energy sources (nuclear, fuel cell, solar, etc.,) - including many not yet in general use. The increasing deployment of electric microwave ovens threatens to undermine much of the use of gas cooking and, consequently, discourage proponents of the
(hydrogen-fueled) flameless catalytic converter. The most critical nonfinancial constraints of electricity generation are control of air pollution emissions at fossil-fuel plants, nuclear power plant siting and waste disposal, and obtaining overhead transmission line corridors. Use of electricity is of course difficult in non-rail transportation applications - although research in battery technologies, though sporadic, has potential.

The potential technical and economic success of nuclear fusion to produce electricity would tend to advance the evolution of an all-electric economy and thereby diminish the future role of hydrogen technologies. The development of long-lived, low-cost, high-energy and power-density electric storage batteries would diminish the long-term need for hydrogen in mobile applications. For example, night-time battery charging would level electricity loads, thereby undercutting a major potential captive use of hydrogen that would otherwise be expected to advance the hydrogen technology state of the art. Development in modest-scale thermal energy storage devices (already in use in Western Europe) would enable electric utilities to further encourage use of electric power for space heating.

iii. Non-Hydrogen Transportation Fuel Technologies

The complete automotive system consists of vehicles, the fuel network, sales and service, and roadways. Competition for the introduction of competitors to petroleum include not only alternative fuel choices but also alternative automotive power plants. Propulsion of ships and trains with hydrogen faces competition from nearly every other fuel, natural or synthetic, except electricity. An exception is for magnetic levitation trains and supersonic aircraft where no other fuel beside hydrogen offers the same hope for use as both fuel and refrigerant for superconducting magnets.

It is expected that consumers will be more willing to pay to maintain convenience, so that the implementation of hydrogen as a liquid fuel and the necessary adoption of new engines and distribution networks would significantly diminish the likelihood that such a change would be preferred to less drastic alternatives. Consumers will favor those options that maximize the flexibility of personal mobility without undue increase in out-of-pocket costs. For example, although the electric car would not preserve the existing gasoline network, in its deployment both the manufacturer and the consumer could be confident about minimal refueling inconvenience. In addition, the electric car would possess clean air attributes at the point of energy end-use comparable to the hydrogen car. Fleet vehicles that operate over long distances, on the other hand, such as intercity trucks and buses, are generally poor candidates for electric propulsion.

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34 The Greening of Detroit, Woodruff, D., Business Week April 8, 1991, p. 56
iv. Non-Hydrogen Fuel Transmission and Distribution

In response to the difficulties and delays in acquiring land for new corridors of overhead power transmission (largely due to both competition for space in densely populated metropolitan regions and to radiation hazard restrictions on nuclear facilities), utilities are showing increased interest in the high-cost technology of underground electric transmission for areas of population density. Because of the more favorable aesthetic impact (underground piping versus high-voltage overhead transmission wires) and reduced commitment of land, it should prove simpler for a utility to secure permission to deploy an underground hydrogen pipeline than to deploy and array of overhead electric transmission towers and power lines. The case of the Little Rock Wastewater Utility is an interesting example of the disadvantages of hydrogen erosion complemented by advances in transmission technologies. The Utility found that its domestic sewer lines, aged 35-50 years and located beneath existing runways and taxiways, were suffering from the effects of hydrogen sulfide deterioration. In response, "the Utility implemented a patented underground pipeline reconstruction process known as Instituform which is nondisruptive by forming a new pipe within the existing pipe" - cost savings estimated at $500,000 per year. 35

Synthetic Petroleum Production Technologies

The petroleum companies can progressively absorb the cost of change and can confine most of it to the portion of the business devoted to resource extraction - allaying the need to discomfort (and lose) customers with significant change entailed in a transfer to hydrogen or other alternative technology fuels. Distributors of natural gas and the gas utilities have demonstrated a priority for investing in synthetic gaseous fuels technologies, focussing on the production of methane as a substitute natural gas (SNG) from coal or lignite (a low-grade form of coal). At the same time, the major oil companies have focussed their resources on "synocrudes", such as coal and oil shale, essentially molecularly identical to conventional fuels - instead of on hydrogen. Combinations of electrolytic hydrogen and heavy hydrocarbons have, in fact, been developed in areas of the world where large amounts of surplus electricity and oil shale or tar sand deposits have been complemented by governmental policies encouraging energy autarky. Examples include large-scale coal liquefaction in Germany in the 1930s and 1940s or in South Africa today.

iv. **Hydrogen Transmission and Distribution Networks in the Hydrogen Economy**

The experience in pipeline transmission of hydrogen in the US is limited to a 50-mile network in the Houston, TX area. Short hydrogen pipelines with operating pressures up to 1200 psia (pounds per square inch) are in use at many refinery and chemical-plant locations. The longest and oldest hydrogen pipeline network is located in the Ruhr area of Germany, where most of a 130-mile network has been in continuous operation since 1940. This network "interconnects 18 industrial plants with 6- to 12-inch pipelines operating at a supply pressure of 150 psia. The pipeline network has no in-line compressor stations and is constructed from seamless steel pipe." 36

i. **Gaseous Hydrogen Transmission and Distribution Networks**

Conversion to a hydrogen economy depends in part on the viability of existing distribution networks in the form of pipelines - largely natural gas. Trunk pipelines are usually constructed of welded steel pipe with diameters up to 48 inches. In the US the lines are 600 to 1000 miles long, operate at line pressures from 600 to 800 psia, consist of more than 350,000 miles of trunklines, and are in reasonably modern condition. Compressor stations (in the form of piston or reciprocating, radial or centrifugal and screw) are located at 100-mile intervals and use a portion of the natural gas in the pipeline for fuel. Because of the lower heating value (325 Btu/SCF (standard cubic foot)) of hydrogen relative to that of natural gas (1025 to 1050 Btu/SCF) approximately 3.2 times as large a hydrogen volume must be transported for an equivalent energy content per unit natural gas. However, the lower viscosity and density of hydrogen allows for a nearly compensating increase in flow capacity so that the same energy-transmission capability is achieved merely by increasing the compressor horsepower by a factor of 5. The energy transmission efficiency of these pipelines is approximately 95% with line losses and compressor consumption accounting for the loss of raw hydrogen material of 5%. 37

ii. **Liquid Hydrogen Transmission and Distribution Networks**

Most of transported liquid hydrogen is used in industrial or research facilities. Liquid hydrogen storage facilities are more easily sited than gas-storage facilities and liquid hydrogen is directly suitable for such end uses as transportation applications. However, the most significant barrier to the use of liquid hydrogen in automobiles would be the establishment of a dense liquid hydrogen distribution network. Fleets of cars, trucks, and buses

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presently consume about 30% of all fuel used in the automotive sector. Because the complications of refueling with either liquid hydrogen or with a low recharging of a metal hybride are less constricting than for fleet use than for automobiles (bulky trucks and buses can more easily accommodate bulky engine structures, fleets operate between fixed-end points and are often idle at night), the use of hydrogen could be implemented far more easily in fleet vehicles than in private automobiles. Trains can carry a large fuel supply and can be operated between fixed, though distant, end-points, thereby greatly reducing the number of fueling points needed. In addition, use of liquid hydrogen would require the use of cryogenic storage vessels, which are likely to remain bulky and costly compared with the simple sheet metal tank commonly used to hold gasoline - and which are also suitable for alcohols like methanol.

iii. **Metal Hybride Transmission and Distribution Networks**

Metal hybrides offer an attractive alternative to liquid hydrogen although many candidate hybrides are incompatible with automotive use. Three options available for distributing and refueling metal hybride beds in automobiles are gas recharge in a filling station, gas recharge in residences, and physical exchange of hybride beds at a filling station. The first two alternatives require either the prior existence of a gaseous hydrogen distribution system or small-scale electrolysis units. The heat transfer problems of a metal hybride recharge suggest that refueling in a filling station might take longer (15 to 30 minutes) than consumers would accept. Recharging at home at night might prove acceptable provided the user never strayed far from home.

Many metal hybrides are unable to release hydrogen fast enough to keep a car operating unless they are held at a high temperature (600 °F). Heat exchangers are not efficient enough to strike the balance needed to release hydrogen in the automotive exhaust system and hydrogen engines are, at the moment, prohibitively large. The heavy weight and large size of an engine needed to contain enough hydrogen to provide a cruising range equivalent to that provided by present automobile gas tanks in full-sized American cars amounts to a prohibitive minimum of about 700 pounds and 11 cubic feet for the lightest candidate hybride, MgH₂. 38

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38 The Greening of Detroit, Woodruff, D., Business Week April 8, 1991, p. 55
v. Safety and Environmental Considerations in the Hydrogen Economy

The basis of all safety considerations in the manufacture, transport, storage and use of large amounts of combustible energy carriers is the determination of their ignition, combustion and potential detonation behavior and the associated pressure build-up in accident situations. Accidents which can lead to the formation of ignitable mixtures are usually triggered by fuel leakages caused by material defects, embrittlement, corrosion, mechanical overload, construction defects, collision (with vehicles) and insufficient maintenance. While climatic impacts of the incremental water loads of a hydrogen economy may be important locally and should be carefully studied, Penner's analysis (p.211) shows that these loads are unlikely to be responsible for significant global temperature or precipitation changes. Air pollution caused by ocean-going ships has not been a problem not because they are non-pollutant - on the contrary, but because most of their operations are far from population centers and, more important, beyond the regulatory control of any government. The electrolytic by-product of hydrogen production, oxygen, could be released into the atmosphere or might be used locally to help clean up waste water or in chemical processes; (depending on economic viability) it could also be transported to serve as an oxidizer for the H2 fuel and thereby prevent the creation of the only pollutant associated with a hydrogen energy system - nitrogen oxide.

Explosion energy, the self-acceleration of combustion processes in totally or partially confined rooms, based on volume is the most serious safety factor when considering the explosion potential of released gaseous hydrogen - when compared with natural gas and propane, hydrogen is lowest. (Please see Appendix 19) With the widespread use of hydrogen in the energy supply system, Dickson et al rightfully suggest that one of the most important safety protection goals is, therefore, to prevent a deflagration (rapid burning without violent combustion) from turning into a detonation (sudden explosion) in rooms, pipeline systems and containers - experiments in which gaseous and liquid hydrogen have been released in the open show that the transition from deflagration to detonation is virtually impossible. Safety considerations therefore are concerned with perfecting internal working mechanisms.

i. Chemical Processes Properties of Hydrogen

The physical and chemical properties of hydrogen, hydrogen combustion properties, and the physical properties of hydrogen fires must be understood before evaluating the safety aspects of hydrogen use. Because of its low viscosity and molecular weight, hydrogen is prone to leakage and, when mixed with air, readily forms

potentially-explosive and easily-ignited mixtures. On the other hand, a hydrogen leak disperses rapidly because of the high diffusion rate of hydrogen gas in air. On a volume basis, three times as much hydrogen as methane will escape through the same orifice. On the other hand, the time elapse before a hydrogen leak produces an hydrogen-air mixture at the upper flammability limit is more than 1.6 times longer than for a methane leak.\textsuperscript{40}

Since the physical and chemical properties of hydrogen are quite different from commonly encountered substances, the hazards associated with hydrogen are to be far more influenced by circumstances its form and environment of use than for other fuels. Although the dangers associated with the use of natural gas, propane, butane, and gasoline have been universally accepted, the trauma of for example the Hindenburg airship fire still burden the image of hydrogen as a prohibitively hazardous material. Public acceptance of the hazards of hydrogen use represent a significant barrier to widespread adoption of hydrogen fuel technologies. The use of liquid hydrogen creates several additional hazard and safety problems.

Additional hazards are associated with liquid hydrogen use because of its high combustibility, low boiling combustibility, and low heat of evaporation. When air is liquefied, because of the difference in the boiling points of oxygen (-297 °F) and nitrogen (-321 °F) the resulting liquid becomes oxygen-enriched. Thus, improperly insulated liquid hydrogen creates local oxygen enrichment - a dangerous fire hazard. The low boiling point and heat of vaporization of liquid hydrogen create serious boil-off problems during storage or handling. Direct skin exposure to liquid hydrogen causes freezing and produces tissue damage similar to that resulting from severe burns.

**Industrial Safety and Environmental Characteristics**

Residential and Commercial operations with hydrogen would necessitate the use of odorants and colorants for safety reasons. Operation of catalytic burners and fuel cells are, however, poisoned (rendered less effective) by the cheapest (sulfur-containing) chemical compounds presently available - a phenomenon likely to be overcome through additional research and development efforts. The odorant and colorant safety additives also affect the potentially large industrial use of hydrogen as a chemical reactant in that chemical purification would be needed to remove the safety additives before hydrogen could be used as a chemical. Although industries normally control the purity of incoming chemicals when they are to be used in high-purity applications, how burdensome an extra cost that would amount to would depend largely on the means of hydrogen production, storage and distribution employed en route to the customer.

ii. Hydrogen Storage Safety and Environmental Considerations

Three key factors affecting the future choice of options for energy storage are geographic suitability, comparative economic cost, and comparative net round-trip energy system efficiency (for example, electricity-conversion-storage-conversion-electricity). There are several optional paths for the round trip between off-peak electricity storage and generation back to peak electricity. The round trip energy efficiency varies according to part and system analysis, but for the liquid hydrogen/fuel cell option it is only about 25% (versus the pumped hydroelectric storage option of 66%). The use of hydrogen as an energy storage mechanism also paves the way for electric utilities to use fuel cells. A final point to consider is the fact that the low boiling point of liquid hydrogen (-423 °F) dictates that particular care must be taken to construct an effectively insulated storage system.

iii. Hydrogen Transportation Fuel Safety and Environmental Considerations

In light of the generally positive space flight experience it can be assumed that hydrogen as a transportation fuel is not at a disadvantage compared to other aviation fuels. Recent analyses and studies performed under NASA contracts whereby it was confirmed that the Shuttle tragedy of 1986 was not only caused by the specific properties of the liquid hydrogen fuel, but that by structural components elsewhere in the aircraft.

vi. Economic Costs of Hydrogen Technologies in the Hydrogen Economy

The entire re-structuring process towards a non-fossil energy economy are tied to cost increases since the manufacture of synthetic energy carriers is inherently costlier than the processing of fossil primary energy. At the same time, however, "the effort to reduce emissions in the the current bills before Congress is estimated to cost about $100 billion over the next 20 years - and will not permanently solve the problem." 41 Economic calculations of the cost of implementing a hydrogen-based economy is in addition to the structural and logistical requirements further complicated by macroeconomic influence over time on capital investment, financing methods (utility versus industrial), interest rates, rate of return on investment, depreciation rates and overhead and liability expenses. The extent and the time-scale on which hydrogen will ultimately become a primary fuel is largely dependent on price developments for hydrogen production, distribution, and application, in relation to price developments for competing fuels and energy supply sources. Secondary considerations will involve revised operations safety assessments and relative environmental-impact analysis.

i. Hydrogen-based Technologies Development Costs

Fuel Cell Development Costs

The use of fuel cells to generate electricity in local substation units, or even in the home or business should be regarded as a realistically implementable hydrogen technology. In addition to savings from increased efficiency in gas utilization, fuel cells by virtue of their being located in close proximity to the user of electricity, achieve additional savings via decreased costs of gas transmission. Although fuel-cell costs in late 1972 were nearly twice as high as other fossil-fuel electricity generating plants on a per kw basis, it is apparent that they become more attractive as fuel costs rise because higher energy-conversion efficiencies to electricity are achieved. High retrofit cost would, however, limit the use of fuel cells to new construction. 42 (Please see Appendix 20)

Photovoltaic Cell Development Costs

The long-term goals for photovoltaics are high efficiencies for cells and modules, good durability and low material and energy requirements not only for the production of cells themselves but for all generator components. Industry capacity cost reductions for photovoltaic (solar) cells tend to follow a 70% decreasing slope with increasing production. For example, in order to achieve market penetration for central-power station applications it is estimated that current costs for space-power stations of $200/w would be reduce to $0.30/w. Diminishing cell thickness and the development of new technologies such as EFG (edge-defined, film-fed growth) should be source of important future costs savings. 43 As Dickson, et al (p. 140) present, the price for electronic grade silicon which so far is the base for crystalline Si solar cells is about $60 to $80/kg., thus, the cost of a solar cell generator is determined largely by the costs of the photovoltaic components.

ii. Hydrogen-based Technologies Production Costs

Although they vary by region, climate, and economic activity, the peak annual demands of most electric utilities usually occur in the summer (because of electric air conditioners) while gas utilities generally experience their peak demand in winter (because of space heating). A combined (electric and gas) utility that sold hydrogen rather than natural gas could load-level electricity in the summer and gas in the winter with the same hydrogen

generation and storage facility - benefiting the economics of hydrogen as an energy storage medium. The elimination of boilers in the hydrogen process heat combustion process must be traded off against the added expense of providing pure oxygen either by purchase, by production in an air separation unit, or by saving and transporting the oxygen coproduced with the hydrogen. Variations in demand necessitate investment in generating equipment sized to meet peak demand which means that much generating capacity is underutilized during slack demand periods while often strained to capacity at peak demand periods.

There is not a good economic match between the normal-sized nuclear power plant and hydrogen pipelines suggesting that utilities have suggested locating a hydrogen-to-electricity generating (fuel cell) facility near the consumer. Realization of this concept would required deployment of hydrogen distribution pipelines in the city to serve the fuel-cell equipped substations. A major drawback to this concept of using hydrogen and fuel cells is the lowered net energy efficiency of delivered electric power. If fuel cell technology were to advance greatly, conversion of gas utilities to hydrogen might be advance slightly. Load leveling, the adoption of a dual pricing structure with lower rates for use of off-peak power (also widely practiced in Europe), would enable electric utilities simultaneously to undercut the gas home-heating market and to help level their load profile. (For a general comparison of fuel production costs, please see Appendix 21)

iii. Hydrogen Transmission Costs

Although the construction of larger diameter cryogenic pipelines will reduce transmission costs, the capital costs of building a hydrogen pipeline inside a liquid nitrogen jacket, not including liquefaction, operation or compressor-fuel costs, is estimated to be about 25 times larger than the corresponding total cost for transmission of gaseous hydrogen. A hydrogen reciprocating compressor for fuel distribution must have 3.8 times the capacity of a natural gas compressor to deliver the same energy content at 750 psia.

iv. Hydrogen Fuel Storage Costs

Conventional cryogenic storage systems as well as compressed-gas cylinders are too expensive for large-scale applications. Instead a jacket containing perlite attractive for minimizing heat losses, while steels or aluminum must be used as liners because of their compatibility with liquid H₂. Large-scale storage of H₂ gas appears to be economically and technically feasible in depleted gas or oil fields, especially as aquifer storage.

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vii. The Dynamics of the Energy Industry

Future energy use can be expected to be a function of population growth, degree of economic activity and energy costs - especially environmental. On the whole heavy population growth leads to a considerable rise in energy use - almost a doubling of world energy consumption must be expected in the next fifty years due to population growth alone. Since industrial countries are still increasing their specific use, though relatively more slowly than the developing countries, the imbalance among these groups of countries is unlikely to decline. Eastern European and some Asian countries will undoubtedly need to invest in a clarification and stabilization of the environmental and occupational health policies of coal mining.

With the electric utility industry at the end of a 20-year construction cycle, few utilities plan to make major additions to capacity in the 1990s. Energy demands are met, now as before, mainly by oil - with an increasing dependence on foreign sources of oil. It provides for 40 to 50% of the commercial energy supply in most countries as well as worldwide. In many exceptionally poor developing countries, oil's contribution to total primary energy usage reaches 85%. About 8100 TWh/a of electricity are used worldwide, ranging from 15 to 20% in industrialized countries and down to a few percent in countries with weakly developed energy supply structures - 30% of that in the USA alone, 20% in Western Europe and 15% in the USSR. In addition, power plants are available with a total production capacity of about 220 GW_e, 23% of which are hydropower plants and 9% nuclear power plants. In some countries ( Brazil, for example ) hydro power provides up to 80% of the power supply.

i. Energy Supply and Demand Structures

In the short-term, coal would be the most economical large-scale primary energy resource for the production of hydrogen. If nuclear power does not develop as planned, electric power generation would have to become even more dependent on coal, thereby limiting the amount of coal available for hydrogen production. In addition, it is expected that nuclear power will in the long term be one of the major primary energy sources for hydrogen. Natural gas is one of the key fuels with which hydrogen would have to compete as transition began. If natural gas is deregulated ( allowing importation of liquified natural gas ), it is expected that demand will fall while supplies and reserves will rise ( owing to increased incentives for exploration ). This would both diminish the size of the gaseous fuel market hydrogen would serve and postpone gas industry interest in hydrogen.

ii. Industrialized and non-Industrialized Countries

Insolation-intensive areas, located usually in developing countries, are required. Hydrogen production plant construction could serve to build up their energy infrastructure and industries. Linked to the export of hydrogen
would be a parallel, mutually beneficial broadening of the international energy market, which could end the reliance on relatively few oil- and gas-exporting countries.

The possibility exists to use hydropower plant energy for hydrogen - by virtue of its ideal energy carrier and storage vehicle - to production in non-OECD nations in order to best compensate for those countries' imperfect infrastructural characteristics. A storage medium is essentially owing to the fact that only a portion of electrical energy generated can be directly disposed of. The remoteness of consumers, the high cost of power distribution over large distances, demand fluctuations and lack of storage facilities contribute to the disruptive dynamic of energy supply in most of the lesser developed regions of the earth.
"It is not enough that hydrogen might be the best final solution; it would also have to be found the best transitional solution. " 45

V. **Conclusions**

This paper has introduced the reader to the currently relevant and multiple technologies associated with hydrogen-powered fuel and chemical processes. In the short run hydrogen will not compete in cost comparisons with hydrocarbon or synthetic-hydrocarbon energy fuels, but its adoption will and should be considered in conjunction with its ideal combustion and non-pollutant characteristics. The findings of the analysis in terms of the large-scale adoption of hydrogen technologies clearly indicate that uncompetitive production costs will, in the short term, inhibit hydrogen's commercial use, particularly as long as the intangible, but real costs of hydrocarbon fuels are unaccounted for. Nevertheless, although the graphic analysis of active researchers in hydrogen-related fields reveals a decline in recent years, inevitably the world's non-sensical reliance on non-renewable energy sources will promote the adoption of hydrogen technologies as finite supply escalates the cost of current resources. The responsible interpretation of a most correct energy resource alternative lies as much with this generation as it does with that of our children's - or that of our children's children.

The hydrogen economy concept is built on the premise that, in the future, when hydrocarbons are not so readily available, hydrogen will be obtainable from water by various means and would eventually entirely replace petroleum-based products. The future costs of delivered hydrogen cannot be completely estimated because costs of storage and distribution are difficult to estimate without design of a detailed system complete with large-scale demand levels. In the very long run, when petroleum, natural gas and coal resources are not available hydrogen will have less competition. During the process of transition, however, hydrogen's ability to compete with alternative energy resources and forms will be crucial to its (interim) survival. Advances in electricity-generating processes and technologies in addition to increasing adoption of conservation products and technologies will challenge that survival in terms of both comparative production costs and decreasing demand for electricity, respectively. (Please see Appendix 22)

In gauging the potential implementation of hydrogen-based technologies, it is necessary to contrast the obvious advantages of hydrogen with the large efforts that would be required for its introduction. Unfortunately, military use of hydrogen seems to compromise, rather than improve, readiness and flexibility - and to increase vulnerability, a significant factor in its ramifications for the evolution of the hydrogen energy economy and reinforcing the importance necessarily placed on civilian-sponsored research and development. Until renewable technologies are proven reliable and economical, most of the hydrogen manufactured will continue to be a by-product of fossil fuels, such as natural gas. The concept of combining electrical-energy and liquid-hydrogen transmission is a promising one for the transmission of liquid hydrogen. For example, liquid hydrogen transmission might be coupled effectively with cryoresistive (-423°F) or superconducting power lines for electrical-energy transmission in an "energy pipe." Development of superconductors with higher critical temperatures may allow replacement of liquid helium by liquid hydrogen as the refrigerant for superconducting
cables. If solar power plants are to contribute to meeting energy requirements of far-distant energy users, their ability to coordinate demand delivery with the limitations of sun-light power generation would be significantly advantaged by the highly efficient, storable and transportable chemical energy carrier - hydrogen. Non-commercial biomass such as inadequate cooking facilities with efficiencies of below 5% of the fuel's heating value have waste resources leading in some places to devastating deforestation. Waste heat from industrially coupled processes, district heating from heating plants or heat pumps today contribute only a very small proportion of the overall heat requirements.

i. The Role of Government

If the hydrogen-based economy concept is ever to be implemented a feasible evolution (small incremental changes) will have to be developed linking the established institutions, short-term investment priorities, interests, biases and social preferences of the present to the future. Because the transition to hydrogen is genuinely only a long-term option and would take more time to implement than the private sector is prepared to be concerned about, the role of hydrogen in the future U.S. energy economy could rely for its survival on public policy geared toward exploiting hydrogen's non-pollutant and permanent resource characteristics. At the same time, as suggested in a Futurist publication "Americans need to recognize the real cost of hydrocarbon fuels and begin to accept - or, in fact, encourage oil taxes and environmental surcharges in order to spur the evolution toward the use of hydrogen - and other non-pollutant fuels." 46

Given the high-level of concern with (and importance of) energy resources, it can be assumed that the federal government will continue to play a big part in future energy policies and prices. Past energy prices have been greatly distorted by governmental regulation - discouraging, for example, in the late 1970s exploration of natural gas reserves due to artificially low price ceilings. Eventual policies will need to contain a combination of incentives to develop new energy sources and incentives to conserve energy with a priority for the development of investment funds among nuclear, solar, geothermal and other technologies. The governments of Japan and Germany have taken the initiative toward alleviating their respective dependence on foreign sources of fuel by promoting research jointly with industry. Recent governmental allocation priorities suggest that, as supplies of natural gas (plus methane SNG) dwindle, consumers "will be denied consumption in roughly the following order: industry that burns methane for heat, including electric generation, industry that uses methane as a chemical source of hydrogen (except ammonia producers), petrochemical industries, ammonia producers, and residential and commercial consumers." 47

Appendix 1

Conceivable Hydrogen Economy Systems


Note: Natural building block sizes in parentheses.
Appendix 2

Non-Fossil Fuel Supply Structures of an Industrial Country


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**Large-scale production**

- Solar energy
- Nuclear energy
- Hydropower
- Coal

**Intercontinental transport**

- Electrolysis
- Liquefaction

**Storage, Conversion, Distribution**

- LH₂ storage
- Underground storage
- Chemical steel industries

**Regional supply**

- Refinery, Liquefaction

**Final usage**

- Transportation
- Power and light
- Space heating, hot water, process heat

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Appendix 3

Worldwide Energy Requirements by Fuel Type


1985
211 Quadrillion BTU's

1995 Mid-Case
253 Quadrillion BTU's
Appendix 4

1985 Consumption of Primary Energy


(Millions of Barrels per Day of Oil Equivalent)

United States

Western Europe

Japan

Less Developed Countries
Appendix 5

Breakdown of How Energy is Used by Six Key Industrial Groupings (1984)


Total Energy Use

OIL USE
Appendix 6

Hydrogen Technology Definitions and Terminology

Battery Technologies
All batteries have drawbacks, and none are suitable for all applications. Batteries can be separated into primary cells and secondary cells. The suitability of cell types for particular applications depends on various cell parameters. In recent years, there has been a search for batteries that have increased volumetric efficiency and longevity. Efforts are being made to make more efficient use of available power so that batteries are becoming the equipment around which equipment is designed. The many different types of batteries include the lead acid cell, the sealed lead acid batteries, leclanche dry cells (zinc/carbon), manganese alkaline cells, mercuric oxide cells, silver oxide cells, nickel cadmium cells, lithium batteries, and nickel hydrogen batteries. 48

Electrolysis
The decomposition of a chemical compound by an electric current.

Energy Efficiency in Electrolysis
The ratio of the energy released from the electrolysis products formed (when they are subsequently used) to the energy required to effect electrolysis.

Energy Conversion
(Indirect energy) Conversion efficiency from chemical (thermal) energy to electrical energy has been limited to 33-45% when conventional boiler steam-turbine-generator systems are employed. Direct energy conversion technologies, in comparison, produce electrical energy from other energy sources, without the intervention of steam generation and the use of conventional steam-turbine generating plants. These technologies include magnetohydrodynamic (MHD) generators, fuel cells, photovoltaic panels, and thermoelectric and thermionic generators - each of these has been employed for specialty uses as well as been considered for large-scale energy-production systems. MHD power conversion and fuel cells serve to increase conversion efficiencies in electricity generation and are designed to make fossil fuel consumption more efficient and thereby alleviate the ever-increasing pressure to find new primary energy sources.

Liquefaction
The major steps in liquefaction of hydrogen are purification, refrigeration, and conversion-liquefaction.

Reforming
Heat is supplied in a series of reactions involving methane, water (steam) and a catalyst. Hydrogen is formed by stripping the methane and water molecules; the reject carbon and oxygen are discarded in the form of carbon dioxide. This reforming process is only about 70% efficient when all the energy inputs needed to complete the complete reformation are considered. Hydrogen produced from methane is the source of the liquid hydrogen rocket propellant used by the U.S. space program and gaseous hydrogen used to synthesize ammonia (75% of which is used in agriculture for fertilizer).

Solar Detoxification
Solar energy could destroy dioxins at 750 °C compared to up to 1,300 °C with conventional incineration and produces almost no harmful products of incomplete combustion. 49

Solar Energy
Solar thermal systems in which sun heat is collected by a wide array device and then concentrated to a smaller point. A second system operates on the photovoltaic principle, which converts solar radiation to dc electricity by the interaction of tiny particles of ultraviolet, visible, and near-infrared light with the electronics in a semiconductor cell. 50

Supercritical Fluids
A substance becomes a supercritical fluid when it reaches its critical temperature and pressure; a solvent in a supercritical state can dissolve substances it could not dissolve under normal temperature. Companies are using supercritical fluids to destroy hazardous wastes; breakdown of hazardous contents occurs because, above critical conditions, water loses its hydrogen bonding ability. Researchers favour the use of supercriticalls as the replacement of distillation, saying that it used only half as much energy. 51

Thermodynamics
That area of physics which deals with heat and its relationship (conversion into) with various other forms of energy, especially mechanical energy.

Water-Splitting Methods
Hydrogen production is achieved from water from conventional or chemical, electrolytic, thermal cycles and hybrid process water splitting methods. Hydrogen production via chemical water splitting is based in

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49 Solar Research Targets Chemical Applications, Parkinson, g., chemical Engineering Vol: 95 Iss: 11, Aug 15, 1988, p. 43
50 New Technology: Sunny Side Up, Tyler, g., Management Services vol: 34 Iss: 9, Sep 1990, p. 26
51 Supercritical Fluids Find Critical Mass, Spalding, B., chemical Week Vol: 140 Iss: 24, Jun 24, 1987, p. 66

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conventional process technology on chemical redox reactions in which water essentially reacts with carbon or carbon monoxide. This method has been replaced for many decades with methods in which steam is converted in heterogeneously catalyzed gas-phase reactions. Thermochemical cyclic processes utilize the coupling of several equilibrium reactions which in separate process steps and at different temperature levels permit the separate release of hydrogen and oxygen. The requirement of several process steps implies complicated process engineering for the total system which frequently places the economic viability of a thermochemical cycle in doubt. Hybrid cycle processes in which one of the partial reactions is executed as an electrolytic step, circumvent this difficulty and are feasible as two-step cycles with attractive overall energy efficiencies.  

### Appendix 7

**Heats of Combustion of Selected Hydrogen-based Fuels**


<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heat of combustion*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^3$ Btu/lb</td>
</tr>
<tr>
<td>C$<em>8$H$</em>{18}$, gasoline</td>
<td>19.1</td>
</tr>
<tr>
<td>C$<em>{0.28}$H$</em>{0.42}$, coal</td>
<td>13.9</td>
</tr>
<tr>
<td>C$<em>{0.32}$H$</em>{0.46}$O$_{0.22}$, wood</td>
<td>7.5</td>
</tr>
<tr>
<td>CH$_4$(g), methane gas</td>
<td>21.5</td>
</tr>
<tr>
<td>CH$_4$(l), liquid methane</td>
<td>21.5</td>
</tr>
<tr>
<td>CH$_3$OH, methanol</td>
<td>8.7</td>
</tr>
<tr>
<td>H$_2$(g), hydrogen gas</td>
<td>51.6</td>
</tr>
<tr>
<td>H$_2$(l), liquid hydrogen</td>
<td>51.6</td>
</tr>
</tbody>
</table>

*Combustion to CO$_2$ and H$_2$O(g), corresponding to the lower heating value, is assumed.*
Electrochemical cell in which a TiO$_2$ electrode is connected with a platinum electrode. The surface area of the platinum-black electrode used was approximately 30 cm$^2$. The symbol $a$ refers to a TiO$_2$ semiconductor mounted on an indium plate, which serves as an electrode contact material. The TiO$_2$ is exposed to light (hv). The symbol $d$ describes an external load across which the voltage was measured with a voltmeter $\mathcal{V}$. The symbol $c$ refers to a platinum-black electrode, while $b$ describes a suitable electrolyte. The elementary processes occurring in the cell are described in the text. Reproduced from Ref. [11].
Appendix 9

Schematic Diagram of Thermionic Power Conversion

Appendix 10

Schematic Diagram of the Ideal Hydrogen-Oxygen Fuel Cell


Schematic diagram of the ideal hydrogen-oxygen fuel cell, used as a source of electrical energy.
Appendix 11

A Summary of Representative Theoretical Fuel-Cell Performance Data


Appendix 12

Diagram of Spherical Liquid-Hydrogen Storage Container

## Appendix 13

### Matching Up Renewable Energy Sources with End-Uses


<table>
<thead>
<tr>
<th>RESOURCE</th>
<th>TECHNOLOGY</th>
<th>ENERGY TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLAR RADIATION</td>
<td>BUILDINGS: ACTIVE, PASSIVE</td>
<td>HEATING, LIGHTING, COOLING</td>
</tr>
<tr>
<td></td>
<td>SOLAR THERMAL: CENTRAL RECEIVER, DISHES, TROUGHS</td>
<td>ELECTRICITY, HEAT</td>
</tr>
<tr>
<td></td>
<td>PHOTOVOLTAICS: THIN FILM, CRYSTALLINE MULTI-JUNCTION, CONCENTRATORS</td>
<td>ELECTRICITY</td>
</tr>
<tr>
<td>BIOMASS:</td>
<td>DIRECT COMBUSTION, BIOCHEMICAL, THERMOCHEMICAL</td>
<td>HEAT, ELECTRICITY, FUELS</td>
</tr>
<tr>
<td>WIND</td>
<td>HORIZONTAL, AND VERTICAL AXIS TURBINES</td>
<td>ELECTRICITY</td>
</tr>
<tr>
<td>OCEAN</td>
<td>OCEAN THERMAL ENERGY CONVERSION (OPEN CYCLE) TIDAL, WAVE</td>
<td>ELECTRICITY</td>
</tr>
<tr>
<td>GEOTHERMAL</td>
<td>DIRECT DRY STEAM, SINGLE- AND MULTI-STAGE FLASH BINARY HYBRID BINARY</td>
<td>ELECTRICITY, HEAT GASEOUS FUELS</td>
</tr>
</tbody>
</table>
Appendix 14

Eras and Events in the Transition to a Hydrogen Economy


- Mature Fuel Distribution Network
  - Railroad
  - Residential Gas
  - Private Auto
  - Short haul Passenger Airplane
  - Coal Gasification
  - Embryonic General Distribution Network
    - Industrial Steam
      - Substitute for Electric Transmission
        - Ammonia
          - Trunk Pipelines
            - Fleet Auto/City Trunk
              - City Bus
                - Highway Bus
                  - Long haul Passenger Airplane
                    - Highway Truck
                      - Electric Utility Load Leveling
                        - Iron Ore Reduction
                          - Stand-alone Production and Consumption
                            - Special Need Uses e.g. Forklifts
                              - Cargo Airplane
                                - Incremental Additions to Existing Production and Distribution Practices

Note: Eras, shown in boxes. Events are shown when 1% market penetration is achieved for realistic scenario.
Appendix 15

A Comparison of Scenarios for Selected End-Use Sectors


<table>
<thead>
<tr>
<th>YEAR</th>
<th>ESTIMATED MARKET PENETRATION</th>
<th>NUMBER OF UNITS AT 1% MARKET PENETRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CITY BUSES</td>
<td>.50%</td>
<td>490</td>
</tr>
<tr>
<td>PRIVATE AUTOS</td>
<td>80%</td>
<td>960,000</td>
</tr>
<tr>
<td>SUBSONIC LONGHAUL PASSENGER AIRCRAFT</td>
<td>80%</td>
<td>9</td>
</tr>
<tr>
<td>GAS TO RESIDENCES, COMMERCE</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>GAS TO INDUSTRY</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>AMMONIA SYNTHESIS</td>
<td>80%</td>
<td></td>
</tr>
</tbody>
</table>

- ○ 1% of potential penetration achieved
- ▲ 10% of potential penetration achieved
- ◆ 100% of potential penetration achieved
- □ Strong government
- ■ Optimistic
- □ Realistic
Appendix 16

Cost Estimates for Producing Hydrogen by Electrolysis of Water


<table>
<thead>
<tr>
<th>Synthetic Fuels Panel (reference 1)</th>
<th>Institute of Gas Technology (reference 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Technology</td>
<td>Advanced Technology</td>
</tr>
<tr>
<td>Time frame for original estimate</td>
<td>1974</td>
</tr>
<tr>
<td>Dollar year</td>
<td>1972</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>Unit cost (cents per kWh)</td>
<td>1.0</td>
</tr>
<tr>
<td>Consumption (kWh per lb)</td>
<td>24.0</td>
</tr>
<tr>
<td>Unit investment cost (dollars per 10^6 Btu per day)</td>
<td>2,440</td>
</tr>
<tr>
<td>Unit operating cost (dollars per 10^6 Btu)</td>
<td>0.36</td>
</tr>
<tr>
<td>Operating factor</td>
<td>0.90</td>
</tr>
<tr>
<td>Fixed cost factor</td>
<td>0.20</td>
</tr>
<tr>
<td>Gaseous hydrogen cost (per 10^6 Btu)</td>
<td>6.52</td>
</tr>
</tbody>
</table>

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Appendix 17

Conceptual Design of a Nuclear-Reactor-based Hydrogen Economy

Appendix 18

Percentage of World Electricity Powered by Nuclear Energy

### Appendix 19

**Safety-related Physical and Chemical Properties of Hydrogen, Methane and Propane**


<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hydrogen $\text{H}_2$</th>
<th>Methane (natural gas) $\text{CH}_4$</th>
<th>Propane $\text{C}_3\text{H}_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density NTP*-gas (kg/m³)</td>
<td>0.0838</td>
<td>0.6512</td>
<td>1.8700</td>
</tr>
<tr>
<td>Self-ignition temperature (K)</td>
<td>858</td>
<td>813</td>
<td>760</td>
</tr>
<tr>
<td>Minimum ignition energy in air (mJ)</td>
<td>0.02</td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>Ignition limits in air (vol.-%)</td>
<td>4...75</td>
<td>5.3...15.0</td>
<td>2.1...9.5</td>
</tr>
<tr>
<td>Flame temperature in air (K)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2318</td>
<td>2148</td>
<td>2385</td>
</tr>
<tr>
<td>Detonation limits in air (vol.-%)</td>
<td>13...59</td>
<td>6.3...14</td>
<td></td>
</tr>
<tr>
<td>Detonation velocity in air (km/s)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.0</td>
<td>1.8</td>
<td>1.85</td>
</tr>
<tr>
<td>Detonation overpressure (bar)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>14.70</td>
<td>16.80</td>
<td>18.25</td>
</tr>
<tr>
<td>Lower heating value (kJ/g)</td>
<td>119.93</td>
<td>50.02</td>
<td>46.35</td>
</tr>
<tr>
<td>Upper heating value (kJ/g)</td>
<td>141.86</td>
<td>55.53</td>
<td>50.41</td>
</tr>
<tr>
<td>Specific heat $c_p$ NTP*-gas (J/gK)</td>
<td>14.89</td>
<td>2.22</td>
<td>1.67</td>
</tr>
<tr>
<td>NTP*-gas (m/s) velocity of sound</td>
<td>1294</td>
<td>448</td>
<td>260</td>
</tr>
<tr>
<td>Stoichiometric mixture in air (vol.-%)</td>
<td>29.53</td>
<td>9.48</td>
<td>4.03</td>
</tr>
<tr>
<td>Diffusion coefficient in NTP* air (cm³/s)</td>
<td>0.61</td>
<td>0.16</td>
<td>0.12</td>
</tr>
<tr>
<td>Explosion energy (kg TNT/m³ NTP*)</td>
<td>2.02</td>
<td>7.03</td>
<td>20.5</td>
</tr>
<tr>
<td>Explosion energy (g TNT/g fuel)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>24</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Explosion energy (g TNT/kJ)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.17</td>
<td>0.19</td>
<td>0.20</td>
</tr>
</tbody>
</table>

<sup>a</sup>NTP: Normal temperature and pressure, 293.15 K, 1.013 bar.

<sup>b</sup>Stoichiometric mixture.

<sup>c</sup>Theoretical maximum; actual value approx. 10% of theoretical maximum.
Photovoltaic Electricity and Solar-Thermal Electricity Costs


Photovoltaic Electricity Costs

Solar-Thermal Electricity Costs
Appendix 21

Production Costs of Energy Contained in Selected Fuels


Production costs of energy contained in selected fuels. The costs apply to large plant capacities, assuming that 15% of the plant cost is allocated annually to profit, interest, depreciation, and maintenance. The cost bases used for the fuels are too low by early 1974 standards. Reproduced from Ref. [2], 1972.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Source</th>
<th>Cost, $/10^6 Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>gasoline</td>
<td>crude oil</td>
<td>1.05</td>
</tr>
<tr>
<td>methanol</td>
<td>natural gas&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>coal&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>lignite&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.25</td>
</tr>
<tr>
<td>ethanol</td>
<td>petroleum feed stocks</td>
<td>4.60</td>
</tr>
<tr>
<td>ammonia</td>
<td>natural gas&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1.57</td>
</tr>
<tr>
<td>hydrazine</td>
<td></td>
<td>21.00</td>
</tr>
<tr>
<td>methane</td>
<td>well-head NG</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td></td>
<td>imported LNG</td>
<td>0.80-1.00</td>
</tr>
<tr>
<td></td>
<td>coal</td>
<td>0.80-1.00</td>
</tr>
<tr>
<td>hydrogen gas</td>
<td>natural gas&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>coal&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>lignite&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.78</td>
</tr>
<tr>
<td>liquid hydrogen</td>
<td>liquefaction</td>
<td>1.50&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Natural gas at $0.40/10^3$ SCF.
<sup>b</sup>Coal at $7/ton$ or $0.27/10^6$ Btu.
<sup>c</sup>Lignite at $2/ton$ or $0.15/10^6$ Btu.
<sup>d</sup>Natural gas at $0.45/10^3$ SCF.
<sup>e</sup>Additional liquefaction cost.
Appendix 22

The Savings of Conservation Technologies - in the U.S. Economy and in OECD Economies

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