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Harvey B. Silverstein

In seeking alternatives to oil to power the world's economies, most public discussion centers on nuclear, solar, wind, water, and coal power. Little considered, because little known, is the possibility of an energy system based on hydrogen. Not the nuclear fusion of hydrogen but its chemical burning. This paper is a primer on such a system. In the author's words, it is an exercise in consciousness raising.

ENERGY SECURITY AND THE HYDROGEN ECONOMY

by

Harvey B. Silverstein

National and international discussions over energy policies have begun to sound more and more like a broken record. In the meantime, the dependency of the United States and many other countries on a few oil suppliers is increasing, while concern over the continuing international diffusion of nuclear power is causing more than a "China Syndrome."

There now exists an opportunity to construct a coherent integrated energy system that would:

1. Make more efficient use of existing sources of energy.
2. Eventually lessen our dependency upon foreign fossil fuel imports.
3. Make far more feasible the application of "soft" technologies to produce energy (solar, wind, tidal, waves, etc.).
4. Create a potential for developing countries that do not have significant fossil fuel reserves to become energy self-sufficient.
5. Create the possibility for *decentralization* in the production and economic control of energy.
6. Create a wider and more dynamic international market for a clean and renewable energy resource.
7. Gradually allow substitution of a perfectly "clean" fuel for the high pollutanr hydrocarbons (coal, oil, gasoline).

This rather impressive set of assertions could be fulfilled through an *energy system* sometimes referred to as the "Hydrogen Economy."[1] It must be stressed that this concept is an energy *system*, not merely an alternative source of energy.

Before proceeding with a blueprint for the Hydrogen Economy, an understanding of the essential division within our national energy debate is critical.

Hard Roads and Soft Paths. With his division of energy development strategies into the "Hard Path" and the "Soft Path," Amory Lovins has attracted wide attention.[2] To put it very simply, the hard path, as an evolutionary line of energy development, involves the continued massive exploitation of fossil fuel resources in large-scale power plants, increased construction of nuclear reactors, possible movement into breeder reactors and eventually nuclear fusion. With some qualifications, this strategy is well reflected by the energy policy objectives whose implementation has been attempted in the United States.

Lovins, as well as many others, have presented eloquent indictments of the hard path as a national objective.[3] To repeat the most important considerations regarding the hard path:

(1) Partly because of the scale and tremendous capital investment required by these facilities, a significant range of technical capabilities, financial controls, and political power is being concentrated in fewer and bigger corporate entities. The oil companies have already taken substantial control over America's coalfields—the largest coal company in the country, Consolidated Coal Company, is owned by Continental Oil Company, one of our smaller oil companies.[4]

Oil companies have also moved extensively into the nuclear business by acquiring ownership of 45 percent of the uranium reserves in the United States.[5] Not many people recognize or appreciate the fact that both Gulf Oil and Shell Oil are partners in the Barnwell Nuclear Fuel Reprocessing Plant, a facility upon which deployment of future nuclear facilities significantly depends.

Some argue that such concentration of energy development is intrinsically bad because of the formation of economic cartels where competition is suppressed and people have fewer choices and less influence over their "energy lives." Others argue that the very size and complexity of the corporate structure make it less flexible and less willing to innovate with a captive market. Supporters, on the other hand, argue that the size and power of the multinational energy corporation are vital assets in dealing with a range of powerful foreign actors.

(2) The second implication of the hard path is environmental. Leaving aside the realities of nuclear releases and nuclear wastes (which would necessitate a lengthy treatise), it is the increased burning of fossil fuels that is causing a problem. Scientists have documented a steady rise in the level of carbon dioxide in the atmosphere since the late 1800s. The predominantly recognized view is that this is a direct result of our increased consumption of oil, natural gas, and coal.[6]

The commonly expressed conclusion is that the rise of CO_2 will cause a "greenhouse" effect, warming the earth's climate, melting polar ice, and resulting in a significant rise in the level of the seas.[7] A series of recent scientific conferences has begun to draw more public attention to the issue of rising atmospheric carbon dioxide levels.

On another environmental front, political and social reactions are already occurring to massive strip-mining, oil drilling and shipment, and uranium exploitation.

The soft path represents a turn towards conservation, recycling, and such renewable energy sources as the sun, wind, tides, waves, and biofuels produced from agriculture and organic wastes. The essence of the soft path consists of far more efficient use of what we now produce, a more conscious fit between energy source and end use, and of individual and corporate determinations, applications, and implementation of decentralized energy systems to match particular needs.

These objectives seem ideal. The problem is that these soft energy sources cannot supply the level of energy we need to run our industries and our country as we know it without an extensive and dramatic rebuilding of our industrial base involving massive capital investment, many years, increased government involvement through sanctions and rewards, and a significant change in basic values on the part of the American people and those of other societies.

The dilemma between the social and environmental costs of the hard path and the political, psychological, and physical barriers to the soft path is endemic to both developed and developing societies. The hydrogen economy can strike a new path, building energy security by making possible the most efficient use of centralized and decentralized energy systems between those of hard and soft.

Hydrogen energy systems can be applied to make substantially more efficient use of the large-scale "hard" sources of energy while also providing the technology to make "soft" sources of energy feasible and more practicable. In a direct about-face from many current trends, the H_2 economy is as relevant and applicable to the developing nations of the South as the highly industrialized high energy societies of the North.

Hydrogen Production. The central feature of the hydrogen economy is the use of hydrogen in gaseous or liquid form as a means of storing and transmitting energy.[8] Hydrogen, itself, represents a near ideal energy carrier. It can be transmitted and burned as a fuel in a manner almost identical to natural gas.[9] When burned as a fuel, hydrogen has the unique characteristic of producing *only water vapor* as a byproduct and *no* carbon dioxide or other damaging hydrocarbon or sulfur pollutants.[10]

Finally, hydrogen can be produced directly from electricity and water by a rather simple process known as electrolysis that disassociates water molecules into elemental hydrogen and oxygen. Although knowledge of this process dates back further than the 1820s, it has been only in the last few years that electrolytic cells with efficiencies approaching 85-90 percent have been developed.[11] In the simplest possible terms this means that very little energy is lost in the conversion from electricity to a hydrogen fuel, contrary to earlier attempts at producing hydrogen. Increases in the operating efficiencies of electrolyzers directly affect, of course, the economics of hydrogen production.

An initial stage towards the hydrogen economy could be the conversion of electricity, specifically offpeak electric power, into hydrogen by electrolysis. Nuclear power reactors and hydroelectric plants usually have load factors somewhere between 0.4-0.7. This means that only 40 to 70 percent of the potential electrical energy is indeed being produced at any given time because these systems are demand-dependent. That is, only enough electricity is generated to meet customer demand. Consequently, a significant portion of the nuclear fuel rods are "burning," and water is going over the dam (in some cases) without doing any useful work. Most of the remaining 30-60 percent of energy now being wasted could be converted directly into hydrogen *with no increased fuel consumption within the system.* Therefore, total energy outputs from nuclear and hydroelectric plants could be increased significantly without additional fuel inputs and cost of additional fuel purchases.

The technology to tap offpeak electricity and produce hydrogen already exists and is being tested by Public Service Electric and Gas of New Jersey, and economic evaluations of a similar system are being evaluated by the Niagara Mohawk Corporation of Syracuse, New York.[12]

The technology for the large-scale production of hydrogen in massive electrolyzers not only exists but has been in place for many years. In this area of research and development the United States has taken a back seat to two of the developing countries. The three largest electrolyzer installations in the world are at Nangal, India; Kima, Egypt; and Norsk-Hydro, Norway. Each of these installations can produce hydrogen at a maximum rare of close to one million cubic feet/hour as a side-product of their massive hydroelectric generating plants.[13]

Brazil and Paraguay are now building the world's largest hydroelectric plant known as Itaipu which will produce an esrimated 70 billion kilowatt-hours per year—almost equal to Brazil's total power output in 1976. Apparently they will be using some rather elaborate new techniques of High Voltage Direct-Current Transmission to move the electric power from its remote jungle site. The Itaipu facility would seem to be a natural for hydrogen transmission of energy, with many profound implications for Brazil. Yet, there seems to be no wide awareness of rhis technology.[14]

The second major source of hydrogen could come from electricity generated by the soft technologies: solar, wind power, warer wheels, tidal power, wave machines and even ocean thermal energy conversion (OTEC). The central problem with all of these soft technologies is rhe intermittenr nature of the energy they are trying to capture. The sun sets and disappears behind clouds; sometimes the wind blows and sometimes it doesn't; waves appear and subside; etc. The principal element that could increase the viability of these small-scale technologies is an effective storage device so that rhe electricity they generate could be "banked" for down periods. Hydrogen generated by compacr electrolyzers can provide that kind of storage device in a rechnological package that could be uniformly applied to a variety of energy generators. Furrhermore, all these sources would then be producing a common form of energy—hydrogen—that would then become a universal fuel. The hydrogen produced by these decentralized systems would also be identical in all characteristics to that generated in the large-scale nuclear and hydroelectric facilities. Therefore, the possibilities exist of wider and more fluid energy markets based upon new compatibilities between "hard" and "soft" energy producers.

The most promising energy sources for the long term (beyond the year 2000) appear to be solar cells and nuclear fusion. Each of these technologies will yield electricity that cannot at present be easily stored in large quantities nor easily used in mobile applications (cars, trucks, boats, airplanes, portable machinery, etc.). The existence of hydrogen distribution sysrems and consumer and industrial goods attuned to the use of H_2 would make the integration of widespread solar electricity and the enormous amounts of energy suggested by the fusion process readily adaptable to national energy systems in use at that time. Particularly in the case of the fusion reactor, a hydrogen production and distribution system would enable decenrralized application of the energy generated with greater efficiency than long-distance rransmission of electricity over wires.

Finally, flexibility in how hydrogen may be generated (nuclear, hydroelectric, solar, windmills, etc.) creates the opportunity for many countries poor in fossil fuel resources to generate considerable amounts of energy by other means. Under certain conditions such a country could become a net exporter of energy in the form of hydrogen. The country of Zaire provides such an example. Under construcrion in Zaire is a series of dams and hydroelectric generators at Pioka, Inga,and Matadi along the lower course of the Zaire River. The amount of elecrric energy that eventually will be generated

> represents the highest concentration of hydroelectric energy so far known in the world, available at costs substantially lower than those of nuclear and conventional thermal power sources . . . and available in quantities exceeding by an order of magnitude the possible demand, even on a long-term basis, of the domestic Zaire market as well as the African one.[15]

The projected capacity of this mammoth project is 57,880 megawatts, which will put Zaire ahead of the United States and behind only China and the U.S.S.R. in total hydroelectric production. There seems to be some intercontinental competition with respect to whether this facility will be larger than the Latin American Itaipu project. The existence of an international hydrogen market would enable Zaire to make far more effective use of this resource.

There are other processes through which substantial quantities of hydrogen can be generated, particularly through the steam reformation of coal and the separation of natural gas. The coal-based procedures could be used in the utilization of remote coal reserves in which the energy would be transported more cheaply as hydrogen gas rather than trainloads or piped slurries of coal. Both these processes, however, would continue consumption of limited fossil fuels for energy production.

Other, more exotic, processes for separating the water molecule are being experimented with by scientists all over the world. Chemical, thermal, thermal-chemical, photo, photothermal, photochemical, thermal-photochemical, biochemical, purely biological, and even laser systems have been demonstrated as being possible and are now being refined. Some hold the promise of being even more efficient than electrolysis under certain kinds of conditions and would apply everything from solar heat to bacterial photosynthesis to the production of H_2. For the present, water electrolysis still remains the simplest and probably the most practical method.

Hydrogen—The Consumption Side. One of the most attractive dimensions of the Hydrogen Economy Concept is the wide scope of uses for the hydrogen. With relatively minor changes in valves, burners, and some pipes, hydrogen can be substituted for natural gas in providing industrial heat and home heating and cooking. Most of the $20 billion capital investment already embedded in the U.S. gas distribution network serving more than 45 million customers would be adaptable to a hydrogen delivery system.[16] Some gas companies are already delivering natural gas with between 3-10 percent hydrogen added as an extender and with no apparent problems. Indeed, the lessons of history can be applied to the piping of hydrogen for domestic and commercial applications because the coal-gas used in many cities at the turn of the century gaslight era was anywhere from 40-50 percent hydrogen.

Today, in Provo, Utah, one of the pioneers of the hydrogen economy, Roger Billings, is living in what he labels the "hydrogen homestead"—a house and a series of vehicles all of which operate on hydrogen fuel. In the beautiful modern home, the space heating, oven, range, outdoor BBQ, and fireplace logs all operate on hydrogen, and the Billings Energy Corporation is now moving ahead with a complete housing development operating on hydrogen. These facilities now depend upon the commercial utilities for electricity to generate the hydrogen which raises the cost of operation above that of standard homes. The future plan is to develop and use a decentralized source of electricity.[17]

A significant part of the hydrogen homestead are the vehicles powered by hydrogen. Hydrogen can be ultimately substituted for gasoline, diesel fuel, and even JP-4 jet fuel. Roger Billings has gained a great deal of attention with his Cadillac Seville, Jacobsen lawn tractor, and U.S. Post Office jeep, which operate effectively on hydrogen without massive engine conversion. Other companies, government agencies, and individuals have applied hydrogen to transportation systems. Mercedes-Benz operates a bus and a luxury sedan running on hydrogen, and the town of Riverside, California, has integrated a hydrogen-powered bus into its public transportation network. The National Aeronautics and Space Administrarion is excited about the advantages to be gained in using liquid hydrogen in aircraft, and the scale model and design for a hydrogen-powered train has been put forward.[18]

Hydrogen Storage. Within the last 6 years the single most important rechnological advance in hydrogen technology has been the development of metal hydride storage. This has made many applications of hydrogen energy practicable. Metal hydride storage consists of small chunks, pellets, or even powder of certain metallic alloys (iron-titanium, lanthanum-nickel, or manganese-nickel are typically used) that absorb considerable amounts of hydrogen like a sponge.[19] The metal hydrides are placed in a canister and hydrogen is pumped in. Some hydrides will store a density of gaseous hydrogen equivalent to that of liquid hydrogen. It is this relatively high storage concentration that makes hydride storage systems particularly appealing for vehicular use. There are two other hydrogen storage alternatives, but both require sophisticated handling and expensive technology. Hydrogen can be compressed in special thick-walled and heavy metal cyclinders (which also requires a gas compressor), or liquefied in special insulated flasks requiring a liquefication facility to produce the cryogenic (very low temperature) liquid.

The Cadillac Seville, Mercedes-Benz sedan and bus, the hydrogen homestead house, and even the offpeak energy storage system being tested by New Jersey Public Service Electric and Gas, all use metal hydrides as their hydrogen storage medium. The most effective method to take advantage of many of the soft technologies may be to couple solar cells, windmills, wave generators, etc., to electrolyzers that then store the hydrogen produced in sizable hydride canisters that can then be tapped as energy demands arise. The liberation of the hydrogen gas from these metal hydrides is, by the way, also quite simple. The application of a small amount of heat (as low as 130°*F*. with some hydrides) causes the hydrogen to gradually release.

This is one of the characteristics that, in certain respects, makes hydride storage canisters even safer than our very familiar gasoline tanks. A recent episode of the excellent *Nova* series produced by WGBH-TV of Boston for rhe Public Broadcasring Service zeroed in on the safety aspects of using hydrogen. In flaming color they performed a series of demonstrations with staged collisions, torches applied to fuel tanks, fuel canisters dropped from heights, and even high-power rifle bullets fired into both the gasoline and hydrogen fuel containers. In virtually every demonstration, the actual and potential damage was markedly less with the metal hydride canisters. Unfortunately, the public's perception of H_2 as a fuel has been most skeptical, primarily because of an incident in Lakehurst, New Jersey, in 1939. The Hindenburg disaster and subsequent replays of this rragedy have given rise to what one sociologist has termed the "Hindenburg Syndrome," whereby the word hydrogen has become synonymous with danger in the public mind. Before there could be any widespread diffusion of hydrogen technologies this perception would need to be addressed. Although materials experts and industrial technologists have clearly established how hydrogen may be safely handled in a wide variety of applications, an extensive program of public education would probably be necessary for practical as well as psychological reasons.

Research on improved hydrides is accelerating in laboratories and by companies around the world to lower their weight and make their storage characteristics equivalent in energy terms to the omnipresent gaoline tank. The hydrides themselves are now commercially available. The MPD Corporation of Waldwick, New Jersey not only has a trade name "Hy-Stor" for its product, but advertises a regular and a higher-performance version that it describes as the "Rolls-Royce" of hydrides![20]

From H_2 to Electricity—The Fuel Cell. One final technological surprise awaits those being seduced by the utilities of this energy concept: The process whereby electricity is used to break down water molecules is reversible so that hydrogen can be combined with oxygen or air in a special type of cell to produce electricity. These cells are called "fuel cells" and are being developed to operate at efficiencies ranging from 50 to almost 90 percent. Therefore, the electrolytic reaction producing hydrogen can be reversed, producing electricity without great energy losses and with no pollution discharge.[21]

The potential applications of fuel cells are considerable and relate directly to the uses of hydrogen introduced earlier in this paper. The utilities experimenting with hydrogen production from offpeak power are also examining the storage of that hydrogen in hydride beds. New Jersey Public Service Electric & Gas and Niagara Mohawk Power are experimenting with reconverting the hydrogen back to electricity through fuel cells to help them raise their generating capacity during periods of peak demand.[22]

Fuel cells would enable an individual residence, office building, or even communities to convert hydrogen generated by their own solar cells or wind turbines or that which is delivered through a long-distance pipeline directly back to usable electricity. The degree to which households, farms, businesses, or industries could generate their own hydrogen would then be indicative of the degree to which they could attain their individual energy independence.

Fuel cells can provide another opportunity. It has been well recognized that the average efficiency of the internal combustion engine of approximately 25-35 percent is inherently low. Electricity produced from a fuel cell and directed through an electric motor can result in a motor vehicle of almost double the efficiency of a normal automobile, with far fewer moving parts and operating far more quietly, while producing zero pollutants.

On a fleet, national, or international basis this means that significantly more people and materials could be moved around on less total energy. A major stumbling block resides in corporate and consumer inertia and in demonstrating that fuel-cell-powered automobiles can match all the performance characteristics of standard gasoline-powered cars. The most significant problem seems to be total fuel storage and, therefore, range of fuel-cell-powered vehicles.

System Implications. Lurking within the concept of the hydrogen economy are two simple, yet very powerful conclusions:

(1) There does exist a means by which national dependencies on foreign petroleum reserves can be lessened.

Clearly, if a nonfossil source fuel can be produced, and if this fuel, hydrogen, can indeed be burned without massive reconstruction of current industrial bases, replacement of household appliances, or shift away from automobile-based transportation systems, then it can be substituted for petroleum fuels if societies are willing to pay the price for conversion.

(2) Contrary to informed public or government perception, there can be created an energy system that will continue and even enhance individual freedom of lifestyle without a dramatic shift towards nuclear fission power reactors or an accelerated exploitation of coal, petroleum, or natural gas and consequently also without their attendant highly centralized corporate and bureaucratic structures.

The concept of the hydrogen economy represents a "synergy," a combination of factors in which the whole represents more than the sum of its parts. We have only begun to uncover the potential synergies of such a system. New technological combinations of various elements of the system beyond those described herein can occur partly because of the inherent simplicity of principles by which hydrogen can be generated, transmitted, and converted to different forms of energy. Of particular interest are the political, economic, and social synergies of such a system, synergies that are not quite so readily apparent.

The 2nd World Hydrogen Energy Conference was held in Zurich, Switzerland, in August 1978. There were approximately 600 scientists, engineers, and even government officials from everywhere from Moscow to Madras. Two features of this global conclave were particularly striking. More than 98 percent of the participants were totally focused upon their specialized discipline or technological device, with little time or active concern for wider system aspects or social, political, and economic implications of their work. Secondly, few scientists and engineers (with some notable exceptions) expressed a desire or interest to communicate with government policymakers or the general public about the nature and significance of their highly specialized work.[23]

While not unusual, these patterns of behavior contribute to the predominant current situation where the hydrogen economy concept is missing from the agenda of national policy debates. The somewhat complicated nature of the hydrogen economy does not lend itself well to simple explanation for a 3-minute newscast or 600 words in *Time, Newsweek, Der Spiegel,* or *The Daily Express*. Consequently, diffusion of the hydrogen economy concept has been minimal to nonexistent. Of course, there is always the possibility of the deliberate suppression of information of the technology itself. Why, for example, has the Internal Revenue Service of the United States specifically excluded "hydrogen fueled residential equipment" from any kind of Energy Credits on its Federal Income Tax forms?[24] In terms of information availability to national and international policymakers, ignorance of the hydrogen system seems likely to be more an error of omission of information in briefings and the policy literature rather than the commission of a deliberate suppression of information. Another simple observation must be made. At no point has a clear, concise and readily accessible version of the hydrogen economy describing its social, political, and economic ramifications been laid before policymakers.

Thus far any mention of the economics of hydrogen energy has been deliberately avoided. This was deliberate because the issue of what is or is not economic is not only very important and complicated, but in constant flux. Nevertheless, there are two fundamental economic questions of concern here:

(1) To what extent can hydrogen systems compete economically or enhance existing major sources of energy (e.g., oil, coal, natural gas, nuclear, and hydroelectric)?

(2) What broader effects would hydrogen systems have upon the existing economic processes and institutions characterizing our energy landscape?

The question of how competitive hydrogen can be with existing energy sources is to some extent a "which comes first—the chicken or the egg" question. Potential producers of hydrogen hesitate to make substantial capital investments in electrolyzers or other H_2 production technology because a defined market does not yet exist. On the other hand, companies that might produce hydrogen-burning technology for consumers will not venture into the marketplace without a guaranteed source of supply.

The cost of producing hydrogen depends totally upon the source. With electrolysis it takes approximately 140 kilowatt-hours (Kwh) of electricity to produce 1,000 standard cubic feet (S.C.F.) of hydrogen.[25] With a range in electricity prices from $.005 to $.08 per Kwh, the cost of 1,000 cubic feet of hydrogen would range from $.70 to $11.20. Natural gas, on the other hand, ranges from a controlled interstate price of $1.75/1,000 S.C.F. to $6.00/1,000 S.C.F. for intrastate trade.[26] However, the hydrogen figures must be multiplied by three to get an equivalent heating value to that of natural gas and therefore the cost of H_2 produced by electrolysis and equivalent to 1,000 S.C.F. of natural gas would range from $2.10 to $33.60. Therefore, the availability of relatively cheap or subsidized supply of natural gas will be a definite disincentive for moves toward a hydrogen economy, while sites of abundant and cheap electric energy could provide an incentive for H_2 fuel production. Most of the millions of cubic feet of hydrogen produced in the United States for industrial purposes now comes from the processing of natural gas. The hydrogen produced by steam reformation of natural gas is still cheaper than that produced by electrolysis, which now supplies only 0.7 percent of total U.S. industrial hydrogen requirements.[27] With increasing pressure on a diminishing supply of natural gas, emphasis is shifting towards coal gasification as a source of hydrogen for industrial processes so that 40-50 percent of U.S. industrial hydrogen requirements by the year 2000 will probably come from coal.[28]

Unfortunately, the substitution of another fossil fuel resource, coal, for petroleum will not resolve the environmental and societal dilemmas set forward earlier in this paper. Hydrogen energy cannot compete effectively with oil, coal, and particularly natural gas, at current prices in most locations. One exception may be hydrogen production and peak-shaving by nuclear and hydroelectric powerplants.

The difficulty in comparing costs of different types of energy comes partly from a plethora of units of measurement so that one must somehow compare barrels, kilowatt-hours, megawatts, thousands of standard cubic feet, short tons, BTUs, and gigajoules. Ultimately, what is most important is the amount of energy delivered per unit (in this case, dollars) of input. The chart below, which assumes certain costs for various forms of energy, gives a ballpark comparison for the amounts of energy obtained per $1.00 of a given fuel.

Energy Output Comparison

$1.00 worth of:

Coal ($30/ton)	=	833,333 BTU
Natural Gas ($.002/cu.ft.)	=	515,500 BTU
Oil ($30/barrel)	=	193,333 BTU
Electricity ($.05/kwh)	=	170,650 BTU
Hydrogen ($.005/cu.ft.)	=	162,500 BTU

The figures given above are, of course, highly variable depending upon the unit cost of the fuels themselves. The chart illustrates that while hydrogen produces the least energy in British Thermal Units (BTU is the amount of energy needed to raise one pound of water 1° Fahrenheit) per dollar of cost, the differences among oil, electricity, and hydrogen are not particularly significant. It must also be remembered that processing, refining, transportation, distribution, and environmental costs are not included in these particular comparisons.

There seems to be a consensus that oil, gasoline, and natural gas, in particular, would have to double or triple their current U.S. prices to make hydrogen competitive. On the other hand, this may well occur within the next 1 to 3 years. Critics of the hydrogen economy concept often dismiss the concept at the introduction of these cost figures. However, what is rarely taken into account is the vast array of semivisible and even hidden government controls and subsidies that make our current energy dependencies more "economic." These range from price controls on domestic oil and the sales of interstate natural gas to oil depletion allowances and uranium depletion allowances as well.[29] The nuclear industry is partially subsidized by the tremendous capital investment made by the U.S. Government in the gaseous diffusion nuclear enrichment facilities at Oak Ridge, Tennessee. There is no space here for an extended analysis of hidden energy subsidies nor their effect on economic competition with conversion to hydrogen. The central argument to be made is that the economic gap between current energy sources and technologically feasible hydrogen systems is (1) narrower in macroeconomic terms than what is generally believed; and (2) could be narrowed still further with either removal of existing energy controls and subsidies or conscious government extension of subsidies to promote hydrogen systems. Subsidies exist, of course, in the form of selective tax writeoffs as well as federal allocations to specified targets. The substantial cost burden of industrial pollution controls would also be considerably reduced where there could be a shift to clean-burning hydrogen.

The costs for large-scale generation of hydrogen are high. Yet, if those costs were incurred in terms of capital investment—a fixed cost, rather than for fuel feedstocks—the long-term economic payoff in a time of continuous inflation should be more substantial. Specifically, investment in large-scale electrolyzers to produce hydrogen at the sites of hydroelectric facilities, such as the massive James Bay dams in Quebec, the earlier mentioned Brazilian and African river projects, the thousands of low-head dam sites in the United States, nuclear power plants, potential large-scale solar, wind, wave, ocean thermal energy converters, and fusion facilities, would enable storage as well as effective use of 100 percent of their power without substantial increase in their operating costs. The energy product, gaseous hydrogen, could be pipelined to consumers at a transportation cost of only 1.5 to 2.5 times that of natural gas, depending on whether existing pipes would be converted or new ones need to be laid.[30] Metal hydride canisters, essential for certain applications, represent additional costs. With mass production, costs could come down to less than $2.00 per pound or about $800 per 400-pound (auto-size) tank.[31]

On the consumption side, costs to convert hydrocarbon (gas or oil)-fueled domestic appliances to hydrogen-burning would be minimal—on the order of tens of dollars per appliance.[32] A converted Dodge Omni automobile, which burns either gasoline or hydrogen at the flick of a switch, is now being marketed for $30,000, including an electrolyzer that produces hydrogen from household current, and the car is capable of 105-mile range at an equivalent of 44 miles per gallon when operating on hydrogen alone. Although this price is relatively high, the producer, Billings Energy Corporation, hopes to reduce the price significantly when a larger-scale (100 Omnis to be retrofitted) production run is undertaken.[33] The key to success in the consumption sector will be whether larger-scale consumer markets for hydrogen can be stimulated.

Societal changeovers from wood to coal, coal to oil and electricity, and from oil to natural gas provide market analysts with full casebooks upon which to base rheir evaluations. Two lessons stand out: these conversions take a long time—an average of 30 years; and these shifts are not based on economic factors alone. The synergistic nature of the hydrogen economy concept, whereby so many factors of efficiency, cost, technological advance, safety, scale, adaptability, use of rare materials, public acceptance, vested interests, and environmental effects are so interrelated, makes the layout of specific cost accounts difficult and perhaps even impossible. Perusal of scores of research studies on hydrogen production, distribution, and consumption suggest that specific costs for the introduction of these technologies would be more expensive than for more conventional energy technologies by a factor of one and a half to three times. With dramatically accelerating increases in oil prices, cost differentials of this magnitude are inhibitive but not prohibitive. Indirect costs such as those brought about as a result of delivery and combustion of fossil fuels, which would not occur in the combustion of hydrogen, have not been included in these cost estimates.

The second primary economic question raised was the effect of the introduction of integrated hydrogen energy systems upon existing economic processes and institutions. Clearly, the apparent potential for bringing about such changes has been a motivating force behind proponents of hydrogen energy systems.

Controversy, emotion and real national security concerns are swirling over the economic predominance of a few oil—now energy—multinationals as well as the economic muscle-flexing of the OPEC cartel. Hydrogen energy systems could serve as a means of diversifying energy supplies and provide a domestic source of fuel to those nations with other sources of probably underutilized electric power resources (hydroelectric and low-head dams, geothermal, wind, solar, tidal, wave, etc.).

On the one hand, decentralization in production and control of energy can take place within a state as many small-scale energy producers begin to use hydrogen storage systems to increase significantly the operating viability of their particular technologies. Decentralized technologies are not only becoming more attractive economically but are also becoming more available. Extensive inventories of these technologies have been published within a variety of sources. A 200-Kwh windmill for $226,000, a complete low-head hydro facility producing 15 Kwh and supplying all farm energy needs from a farm pond for a total investment of $15,000, and a corporate prediction of expected developments in solar cells to lower busbar electrical generation costs to $.05/Kwh are particular examples pointing towards successful production and diffusion of decentralized energy technologies.[34]

On the other hand, small-scale producers can integrate among themselves and even engage in H_2 product sales or purchases to or from the big energy multinationals or public utilities because of production of a common, uniform, readily interchangeable energy product. With hydrogen, there is no delicate coordination of cycles per second as is the case with electricity or the careful chemical match-up necessary in combining certain stocks of crude oil or refinery products.

In contrast to the present constriction in terms of international management and ownership of energy supplies, development of a hydrogen economy should stimulate a much broader market with far more participants at all scales, while not disenfranchising the existing corporate or public utility enterprises operating today. The energy market would become far more dynamic while evolving towards the concept of a universal fuel. With a greater number of states having a potential for producing such a fuel and a common fuel coming into demand for everything from vehicles to residential heating, considerably wider markets would also open up for producers of the equipment utilizing hydrogen fuel. At present, differences in voltage and cycles per second, gasoline formulas, and makeup of natural gas supplies serve as constraints in the direct transfer of technology from one country to another.

The relative simplicity of the technologies involved in the production and distribution of hydrogen not only makes them particularly suitable for countries without a sophisticated technological base, but also makes these technologies highly adaptable to change. In an age when generational changes in go-go technologies can occur in as little as 18 months, an inherent receptivity to innovation is becoming vital. The decentralized nature of the hydrogen system makes innovation of particular elements a far simpler process than, by contrast, a change in the operating elements of a large-size nuclear reactor.

A final major and salutary effect on our social and economic system could take place by a large-scale transfer to utilization of energy in the form of hydrogen. Burning of hydrogen in lieu of gasoline, fuel oil, and coal would dramatically lower the discharge of a wide range of noxious pollutants in the atmosphere. Already, recognition of this relationship has resulted in the Riverside, California City Council, the Chamber of Commerce, the Lung Association of Riverside, and the California Medical Association to push for and secure legislation to obtain state funds for the purchase of a hydrogen-powered bus as a demonstration project. Their motivation was specifically directed at developing smog-free vehicles, and their eventual findings were that "if more such vehicles were converted to operate on hydrogen the smog problem would virtually be eliminated."[35] There is every reason to believe the direct health effects as well as medical costs, pollution abatement technologies, industrial monitoring and conversion expenses, government surveillance and administration, and permitting procedures and expenses could all be significantly reduced with a move away from fossil fuels. The longer-term problem of global atmospheric carbon dioxide buildup may also be ameliorated to the degree that the hydrogen economy concept is adopted internationally.

It would be in the highest national interest of the United States as well as many other countries to incorporate the hydrogen economy concept as a national policy objective. The dynamics of hydrogen energy technologies can create economic relationships with highly desirable social and political results:

1. Make more efficient use of existing sources of energy.
2. Eventually lessen our dependency on foreign fossil fuel imports.
3. Make far more feasible the application of "soft" technologies to

produce energy (solar, wind, tidal, waves, etc.).

4. Create a potential for developing countries that do not have significant fossil fuel reserves to become energy self-sufficient.

5. Create the possibility for *decentralization* in the production and economic control of energy.

6. Create a wider and more dynamic international market for a clean and renewable energy resource.

7. Gradually allow substitution of a perfectly clean fuel for the high-pollutant hydrocarbons (coal, oil, gasoline).

To create an incentive to stimulate discussion and attention in this country, we may borrow a lesson from the U.S. military and briefly describe what the Russians are doing. For the past 2 years hydrogen energy has been a major subject of concern at a series of international seminars held at the I.V. Kurchatov Institute of Atomic Energy in Moscow and chaired by the President of the U.S.S.R. Academy of Sciences, Academician A.P. Alexandrov.[36]

Hydrogen production, distribution, applications, and engines were among the subjects discussed. Although we have also had conferences, publications, and even television specials, the nature of the hydrogen economy has unfortunately remained "below the level of visibility of decision-makers," both here and abroad.[37]

Once the Hydrogen Energy System does become a national objective, policies can then be developed to accelerate the acceptability and economic feasibility of these technologies. Embodied in the very nature of the hydrogen economy is the potential for stimulating far more economic competition in economics stifled by energy cartels, and simultaneously permitting a basic flexibility that will be open to and even reinforce the technological innovations of the 21st century.

BIOGRAPHIC SUMMARY

Harvey Silverstein was educated at the University of Wisconsin, Hebrew University, and the University of Denver, receiving the Ph.D. degree from the latter. He has been a research fellow at the Harvard Center for International Affairs, Woods Hole Oceanographic Institution, and NASA and a consultant for the National Science Foundation. He has taught at the University of South Carolina and is now Visiting Associate Professor in the Department of Political Science at Dalhousie University. His articles have appeared in *Annual Proceedings of the Marine Technology Society* and *Journal of Maritime Law and Commerce* and he is the author of the recent *Superships and Nations-States—The Transnational Politics of IMCO.*

NOTES

The author is extremely interested in military applications of hydrogen energy and would welcome ideas or information relevant to naval or other military systems.

1. The earliest reference to the system concept of the H_2 Economy that I have been able to find is Derek P. Gregory, "The Hydrogen Economy," *Scientific American,* January 1973. It has been suggested, however, that Jules Verne is the real father of the Hydrogen Economy.

2. It began with his article "Energy Strategy: The Road Not Taken," *Foreign Affairs,* October 1976, pp. 65-96, and continued with a spate of articles and books further developing these themes.

3. See also Wilson Clark, *Energy for Survival* (Garden City, N.Y.: Anchor Press, 1975), and Denis Hayes, *Rays of Hope* (New York: Norton, 1977).

4. See James Ridgeway, *The Last Play* (New York: New American Library, 1974), for extensive detail on concentration and ownership of world energy corporations.

5. *Ibid.,* p. 158.

6. *Scientific American, Technology Review, Science* and countless Government Reports and other sources have discussed this issue in news reports, technical articles, scientific debates, etc., over the last 10 years.

7. Some scientists, however, conclude exactly the opposite and postulate that increased CO_2 levels—which is agreed upon—will result in climate cooling.

8. I am using the terms "hydrogen energy system" and "hydrogen economy" interchangeably to represent an overall macrolevel design concept. "Hydrogen energy system" could, of course, also be applied to an individual configuration of technical devices in a given location.

9. On a per volume basis, the heating value of hydrogen is 325 BTU/S.C.F. while that of natural gas ranges between 950-1,000 BTU/S.C.F., which means that an increase in operating pressure would be necessary to maintain equivaleot energy flows in a gas pipeline. See J.P. Pangborn, et al., "Gas Distribution Equipment in Hydrogen Service, Preliminary Findings," in *Hydrogen Energy System*, Proceedings of the 2nd World Hydrogen Energy Conference, Zurich, Switzerland, 21-24 August 1978 (New York: Pergamon Press, 1979), v. 3, pp. 1329-1346.

10. Under high temperatures and in some applications nitrous oxides can be produced, but technologies for eliminating the formation of these byproducts have already been developed.

11. Theoretical efficiencies clearly approach 100 percent. See Alex J. Konopa and Derek P. Gregory, "H_2 Production by Electrolysis: Present and Future" in *Record of the Tenth Intersociety Energy Conversion Engineering Conference*, Newark, Del., 18-22 August 1975 (New York: Institute of Electrical and Electronics Engineers, 1975), pp. 1184-1193.

12. See J.M. Burger, "An Energy Utility Company's View of Hydrogen Energy," *International Journal of Hydrogen Energy*, Jan-Feb 1976, pp. 55-64, and R.A. Fernandez, "Hydrogen Cycle Peak-Shaving for Electric Utilities," *9th Intersociety Energy Conversion Engineering Conference Proceedings*, San Francisco, Calif., 26-30 August 1974 (New York: American Society of Mechanical Engineers, 1974), pp. 413-422.

13. Konopa and Gregory, p. 1190.

14. See "Itaipu: Direct-Current Transmission," *Science*, May 1978, p. 754.

15. G. Livadiott, et al., "The Hydroelectric Potential of the Lower Course of the Zaire River and Possible Uses of the Electric Power," *Hydrogen Energy System*, v. 1, pp. 173-192.

16. Pangborn, et al., p. 1329.

17. Roger Billings, "Hydrogen Homestead," in *Hydrogen Energy System*, v. 4, pp. 1709-1730.

18. Not only have detailed designs for hydrogen-powered aircraft been developed, but alternative plans for airports and support facilities as well. See K.S. Varde, "Hydrogen Fuel in Air Transportation and Its Effects around Airports," in *Hydrogen Energy System*, v. 4, pp. 1903-1916, and G.D. Brewer, "Aviation Usage of Liquid Hydrogen Fuel—Prospects and Problems," *International Journal of Hydrogen Energy*, Jan-Feb 1976, pp. 665-68. For discussion of rail applications, see R.T. Alpaugh, et al., "Hydrogen-Fueled Railroad Motive Power Systems—A North American View," in *Hydrogen Energy System*, v. 4, pp. 1793-1828. The literature on automotive applications for hydrogen fuel is already immense. For a description of the particularly interesting and sophisticated approach taken by Daimler-Benz (Mercedes), see H. Buchner and H. Saufferer, "The Hydrogen/Hydride Energy Concept," in *Hydrogen Energy System*, v. 4, pp. 1749-1792.

19. Literature on metal hydride storage is accumulating rapidly. See F.E. Lynch and E. Snape, "The Role of Metal Hydrides in Hydrogen Storage and Utilization," in *Hydrogen Energy System*, v. 4, pp. 1475-1524.

20. "Hy-stor Metal Hydrides—A Revolution in Hydrogen Storage Technology," company brochure (Waldwick, N.J.: MPD Technology Corp.).

21. Van de Broeck, et al., "Prospects for an Alkaline Hydrogen Air Fuel Cell System," *Hydrogen Energy System*, v. 4, pp. 1959-1969, sets forth the potential for large-scale use of fuel cells within the European Community.

22. See Fernandez; Beaufrere, et al., "Hydrogen Storage Via Iron-Titanium for a 26 MW Peaking Electric Plant," *International Journal of Hydrogen Energy*, Jan-Feb 1976, pp. 307-319.

23. I observed an identical phenomenon in a different context while living for a year among a community of marine scientists at the Woods Hole Oceanographic Institute.

24. See *Federal Income Tax Forms*, Form 5695-Energy Credits.

25. This assumes an overall operating efficiency of 30 percent—common with production technology. Newer electrolyzers are operating close to 80 percent efficiency, which means of course a substantial decrease in the number of kilowatt hours (110-120) necessary to produce the same amount of hydrogen.

26. Natural gas prices are often quoted in terms of dollars/million BTU, but because there are roughly 1,000 BTU/cu. ft. of standard natural gas, the figures can be viewed as equivalent. For a comprehensive report on pricing and shipment of liquefied natural gas, see U.S. Congress, Office of

Technology Assessmeot, *Transportation of Liquefied Natural Gas* (Washington: U.S. Govt. Print. Off., 1977).

27. C.J. Huang, et al., "Demand and Supply of Hydrogen as Chemical Feedstock in the U.S.A.," *International Journal of Hydrogen Energy*, Jul-Aug 1979, pp. 287-296.

28. *Ibid.*, p. 295.

29. See Ridgeway for extensive discussion of the nature of such subsidies and how they came about.

30. Y. Breelle, et al., "Technico-Economic Study of Distributing Hydrogen for Automatic Vehicles," *International Journal of Hydrogen Energy*, Jul-Aug 1979.

31. Personal communication from E. Snape, General Manager, Ergenics Division of MPD Technology Corporation, Wyckoff, N.J., 20 August 1979. The price refers to iron-titanium alloy; other alloys may be more costly.

32. See N.R. Baker, "Oxides of Nitrogen Control Techniques for Appliance Conversion to Hydrogen Fuel," *9th Intersociety Energy Conversion Engineering Conference Proceedings*, pp. 463-467.

33. "The Car With a Future: Hydrogen Powered Dodge Omoi," *Hydrogen Progress*, Spring 1979, pp. 17-32.

34. Private correspondence, Alfred Gross, Director of Marketing, WTG Eoergy Systems, Inc., Buffalo, N.Y., 24 July 1979. For an excellent overview of low-head dams (almost 3,000 in New England alone), see David Sylvester, "Big Dreams for New England's Little Dams," *Yankee Magazine*, November 1977, pp. 126-133, 181-190. A detailed economic analysis of solar cells is found in H.J. Hovel, "Novel Materials and Devices for Sunlight Concentrating Systems," *IBM Journal of Research and Development*, March 1979, pp. 112-121.

35. Dr. Robert M. Zweig was particularly instrumental in this effort and has spoken of this project in many contexts. See his editorial, "The Riverside Bus—Only the Beginning" in *Hydrogen Progress*, Spring 1979, p. 32.

36. "U.S.S.R. Seminars on Atomic and Hydrogen Energy," *International Journal of Hydrogen Energy*, July-Aug 1979, p. 49. Selected papers from these seminars have been published io *Voprosy Atomnoi nauki i Techniki* and *Atomnovodorodnaya energetika i tekhnologiya*, Moscow, N1, 1976, N1(2), 1977, N2(3), 1977 and N4, 1978.

37. Alpaugh, et al., p. 1797.