NUCLEAR ENERGY, ENVIRONMENTAL PROBLEMS AND THE HYDROGEN ENERGY ECONOMY

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I. Introduction

The virtues of hydrogen as a fuel have been long appreciated [1], but it must be prepared from natural gas, the most economical current source. Anxiety about fossil fuel depletion, atmospheric pollution and global warming suggest hydrogen prepared from ocean water (by electrolysis). Inexhaustible, excellent for energy storage and transmission, and environmentally benign, tt can be burned in fuel cells or other. Chemically versatile, it combines with atmospheric nitrogen to yield ammonia for fertilizer, a fuel much like hydrogen and a refrigerant not depleting the ozone layer. In the petrochemical industry it upgrades heavy tar fractions to gasoline and catalytically converts coal or peat to methane. A good reducing or hydrogenating agent, it can replace carbon in reducing ores to metal. Its main drawbacks are cost and needing more energy to produce it than is released by combustion.

The objections are now less compelling because meeting environmental concerns and fuel depletion raise cost, and conversion loss can come from renewable energy. Our "navel estimate" (made by navel contemplation until estimates materialize) of conversion cost is trillions of dollars. This demands synergies and intelligent planning.

The plan of this paper is as follows. Part II gives some synergies and hydrogen demands which help drive the transition. III argues that renewable-based hydrogen can satisfy foreseeable energetic and environmental demands. IV considers the role of non-renewables, V, financing, and VI, some conclusions, questions and prognostications.

II. Projected Hydrogen Demands and Possible Synergies

We give navel estimates of hydrogen requirements. The U.S. consumed under 80 quad in 1973, so 1000 quad for world energy demand does not seem absurd. As one quad is 2.93×10^{11} kwh and there are 8766 hr/yr., we need under 5×10^{10} kw, or 50,000 continuously running plants, each delivering 1000 megawatts. Round to 10^5 plants (for downtime, etc.). If each plant costs 10 billion dollars and we allow another order of magnitude for other infrastructure, we get a navel estimate of a trillion dollars.. This should be supportable over perhaps 50-100 years, (which is also a ball-park estimate of how long fossil fuels will last).

The place to start is with large hydrogen consumers who need it with less atmospheric pollution. Electrical utilities use hydrogen from methane in fuel cells for peaking capacity, producing carbon dioxide. Anxious to reduce it and other pollutants, they are wind power pioneers and logical spearheads for constructing wind turbines to provide on-line power and hydrogen generation. Government tax and depreciation policy, like super-accelerated depreciation of fossil fuel burning equipment to the full cost of the wind machines or other renewables replacing it, plus removing limitations on commercial sales of hydrogen would encourage utilities to be hydrogen based and hydrogen suppliers.

Co-generation can include hydrogen. The utilities and the ammonia industry can do it. Liberal depreciation and tax policies to shift from methane-based to renewables-based hydrogen, plus laws or taxes discouraging carbon dioxide generation, would push the hydrogen plus ammonia economy. Ammonia might rival hydrogen because ammonia-fueled cars have greater range than hydrogen-fueled cars. They substitute tank ammonia storage for cryogenic, high- pressure, or metal-hydride hydrogen storage [2]. The case for hydrogen is stronger for planes, ships, trains, buses and trucks vis-a-vis ammonia, especially planes (where liquid hydrogen is a better fuel than hi-test gasoline [3].

Hydrogen and ammonia are probably less hazardous than gasoline. Choice between ammonia and hydrogen depends strongly on application conditions. Low usage rates, long storage times, low weight and capability for immediate stand-by use probably favor ammonia. Large scale, stationary applications (like utilities) favor hydrogen on a cost basis. Ammonia is a light weight, stable, (but not too stable) hydride, competitive with metal hydrides.

Much pollution and greenhouse gas comes from smelting operations, so replacement of carbon by hydrogen could be helpful. A metal oxide ore MO reduces to metal M according to

$$MO + H_2 \rightarrow M + H_2O \uparrow \quad (1)$$

The corresponding carbon reduction produces carbon dioxide

$$2\,MO + C \rightarrow 2M + CO_2 \uparrow \quad (2)$$

If the reaction is incomplete, poisonous carbon monoxide is produced by

$$MO + C \rightarrow M + CO \uparrow \quad (3)$$

Water from (1) is benign, could be useful, and would cause negligeable rust in an H_2 atmosphere.

Spectacular improvement may result with sulfide ores. Current "roasting" produces sulfate particulates and acid rain. With hydrogen, sulfide reduction obeys

$$MS + H_2 \rightarrow M + H_2S \uparrow \quad (4)$$

This would be done in a closed system, for H_2S is the poisonous foul-smelling essence of rotten eggs. It easily decomposes into its elements

$$H_2S \rightarrow H_2 \uparrow + S \downarrow \quad (5)$$

regaining the original hydrogen (theoretically all is possible), which can be recirculated, and produces elemental sulfur which may be needed for sodium-sulfur cells in electric vehicles and elsewhere. The sodium (from brine) would be a by-product of making electrolytic hydrogen from sea-water. The hydrogen economy thus seems likely to reduce or eliminate most of the contributions to pollution, global warming and acid rain ascribable to metallurgical operations. The metals industry has a vital stake in hydrogen to avoid environmental shut-down of some smelters.

The fossil fuel industry should not try to abort the hydrogen economy as a dangerous rival, for its stake may be even greater than those of industries already considered. The greatest producer and consumer of hydrogen is the oil industry. It uses natural gas, formerly flared off, as a source of hydrogen to convert heavy oil fractions into valuable liquid fuels. When oil depletes, the only way for the petrochemical industry to prolong its existence (other than by becoming appendages of Gulf oil monopolies) will be by liquefying heavy oil fractions, tar sands, oil shale, coal and peat, by hydrogenation with electrolytic hydrogen. The petrochemical industry may therefore become a main mover toward the hydrogen economy. This is not certain because foreign oil may apply pressure to hold back the transition. This strategy can not succeed in the long run, so cooperation and participation should be seriously considered as a matter of self-interest.

With methane, two moles of hydrogen burn for each one of carbon:

$$CH_4 + 3\,O_2 \rightarrow 2H_2O + CO_2 \quad (6)$$

Burning a long chain hydrocarbon combusts CH_3^- end groups, and possibly many intermediate - (CH_2) - groups. Combustion of a pair of them obeys

$$2\,(CH_2) + 3\,O_2 \rightarrow 2\,H_2O + 2\,CO_2 \quad (7)$$

doubling the ratio of CO_2 to H_2O. For coal, the hydrogenic contribution is nil. All the energy comes from exothermic production of CO_2 :

$$C + O_2 \rightarrow CO_2 \quad (8)$$

All other hydrocarbons fall between (6) and (8).

Reducing the amount of carbon dioxide per BTU is done by hydrogenating the hydrocarbons as much as possible. Methane has the highest degree of hydrogenation. The opposite extreme from (8) is the combustion of hydrogen

$$2H_2 + O_2 \rightarrow H_2O \qquad (9)$$

producing no carbon dioxide at all.

Combustion of ammonia obeys

$$2NH_3 + 3\,O_2 \rightarrow 3\,H_2O + 2\,N_2 \qquad (10)$$

The nitrogen is a hydrogen "container" which returns to the atmosphere. Methane carbon is a burnable hydrogen container, holding more hydrogen than metal hydrides or ammonia. It can be manufactured catalytically from carbon. Practicality as a low pollution auto fuel has been demonstrated, but fossil methane will eventually be exhausted. If electrolytic hydrogen reduces the carbon dioxide burden from non-automotive sources, and methane largely replaces gasoline, the carbon dioxide burden imposed by it and some other hydrocarbons may become tolerable. The possibility of electric vehicles, battery or hydrogen fuel cell driven, and vehicles burning hydrogen or ammonia make this plausible. In any case, the time to switch from gasoline to natural gas has come. When methane threatens to run out we can decide whether to manufacture it, go the electrical route, or use hydrogen or ammonia.

Coal and peat are bad polluters, but by catalytic hydrogenation they provide methane and hence, organic chemicals. Their future lies here; the same is indicated for tar sands, heavy oils, tight shales, etc.

III. Whence All the Needed Electrical Energy?

Man's activities affect the whole earth and bad unintended consequences can stem from actions deemed harmless at the time they were begun,. We try to minimize them by studying possible environmental impacts beforehand. Hydrogen needs so much energy that we must consider the impact of tapping it. This may seem odd for how can tapping the energy of wind, water, and sun be other than harmless? What of geothermal and nuclear energy? Is the latter always an environmental nightmare? Just as we must try to avoid deleterious environmental impacts, so must we avoid unjust blanket condemnation of energy sources whose bad effects may be avoided with proper precautions. We can not afford to be blinded by ideologies, no matter how seductive, if we are unable thereby to benefit from actions not harmful when done properly. We must base our decisions on good science, do more research if current knowledge is insufficient, and reverse course if new dependable knowledge discloses bad effects of an accepted modus operandi. When we press the limits of what the planet can provide we can not afford the luxuries of stupidity or self-inflicted blindness.

Wind, water and sun are the obvious sources of renewable energy (geothermal energy is really a fossil resource); consider them in order. Is there enough wind energy to support the hydrogen economy, and can we tap that much with impunity? Old surveys suggest that U.S. wind resources can supply all needed energy. World resources should suffice for world needs. The real estate required, the noise, the dangers of blade failure and hazards to wildlife argue for remote siting. Maximum wind turbine power goes as the cube of wind velocity [5], which is an order of magnitude greater in and near Antarctica than in the continental U.S.A. Megawatt ratings achieved in the U.S.A. [4] become possible terawatt ratings for Antarctic wind machines. Single machines with output comparable to nuclear plants are then not ridiculous a priori. If we take 10^7 mi^2 as the area of Antarctica and surrounding ocean (over which circumpolar winds blow almost continuously), the 10^5 machines of II can be sited on land or sea with room left for 10^6 more! Wind energy alone should suffice for the world's needs indefinitely.

What might be impacted by 10^6 big machines? We usually assume that the earth's wind system is driven by the sun, but how much of it would still operate if the earth no longer rotated? Could the 10^6 machines be a frictional drag on the earth's rotation, in effect "mining" its kinetic energy of rotation? Would this be negligeable or significant compared to the frictional drag already imposed by earth's wind and tidal systems? The day has been slowly lengthening for eons, so this is probably not a severe worry. The combination of modern atomic clocks and precision astronomical observation may permit us to measure small fluctuations in the earth's angular velocity. When this has been done we will know what risks we run.

Similar analysis can be made of energy from the hydrosphere. Solar energy evaporates ocean water, which condenses as rain and runs back to the ocean via rivers. This is, of course, the basis of hydroelectric power, which currently taps but a tiny fraction of the kinetic energy of the hydrosphere or of falling rain. In medieval times, watermills in anchored boats in rivers, run by paddle wheels, were common. They tap the kinetic energy of flowing water without dams. How many orders of magnitude greater than the total output of all dams might energy from this one source be? Essentially all rivers may be harnessed this way. Remoteness and intermittent operation is no problem with hydrogen. Catching rain over wide areas which drain into vertical pipes feeding turbines may have much potential, particularly in rain forests and at sea. Could the Maelstrom and other natural or artificial tidally fed whirlpools become significant energy sources? Are there not tens of thousands of locations where tidal energy is suitable for hydrogen production though not for power generation tied directly to grids? Can not the Gulf Stream and other ocean currents drive relocateable watermills? Are not essentially all proposals so far to tap ocean wave and tidal energies more suited to hydrogen generation than to direct power grid hook-up? Are not "salt tongues" and thermal upwellings additional candidates for hydrogen generation? An outstanding example of the first occurs near the Straits of Gibraltar. Dense saline water flows out of the Meditteranean and down the continental shelf while less dense Atlantic water rides back in over it. The bottom current reaches 1.3 meters/sec and the volume must be immense [6]. To how many Niagaras is this flow equivalent? Water mills or turbines 1000 meters below the surface or floating could well supply vast amounts of hydrogen. Why not tap hot rising water above thermal vents to drive turbines? Other schemes, like OTEC, seem more practical for generating hydrogen than for feeding a grid.

It seems likely that the world's water can deliver as much or more power than its winds. The part involved in the evaporation cycle would presumably not be closely coupled to the earth's rotation, though the tidal part might. Discussion of that part could recapitulate what we said about wind energy in that regard. It might also couple to the earth-moon system. All this would have to be studied with care. However, much energy can surely be supplied before any deleterious effect could even be detected.

Solar energy splits on earth into thermal and photonic components, the latter being the part used for its photovoltaic effects in semiconductors. It is essentially uncoupled to the earth's rotation (except for time of availability), and often taken as virtually synonymous with solar energy. Bad effects seem to be mostly restricted to requiring large amounts of real estate, device cooling, and capital investment. The first is ameliorated by desert or ocean siting, the second by ocean siting, and the third is essentially why (as of 1993) wind energy seems more practical. Research is active and the situation can change.

The thermal part includes such things as space heating, solar distillation, solar steam engines, drying operations, solar ponds and the like. These are benign and related to the theme of this paper because they reduce the demand for fossil fuel. Their significance should steadily increase.

Lastly, consider nuclear energy. If not for fear of accidents and radioactive waste, even environmentalists would admit that nuclear energy poses few problems for the environment compared to fossil fuels. Cohen [7] has discussed irrational public attitudes about them. Many scientists look at the waste problem as more political than technical (the acronyms LULU NIMBY NIMTO often come up, standing respectively for local unwanted land use, not in my back yard, and not in my term of office). Remote siting, say at sea, avoids the acronymic bugaboos, leaving only the waste disposal problem. Design ships, platforms and reactors to allow the whole reactor to be jettisoned at the end of its life into a hole on the sea bottom. Let the portion of the earth's crust containing it be destined by plate tectonics to be buried deep in the earth. It would then take billions of years for the reactors, dissolved in magma, to surface in lava flows. By then it would be safe. Nuclear energy can thus help phase in the hydrogen economy over a long enough time to build needed renewable infrastructure at an affordable rate. It is doubtful if we can afford not to use it.

If environmentalists really believe it necessary to eliminate fossil fuels they should enthusiastically support a hydrogen scenario. The alternatives seem to be either impractical (economically or technically) or to require too long a continued reliance on fossil fuels (which may not even be available), uncomfortably continued pollution and global warming. Another synergy of the nuclear scenario is that ocean water reactor coolant could be input to multiple stage distillation plants, supplying large amounts of fresh water to a thirsty world. Currently the bulk of water distillation in the world occurs in oil-fired plants in the Persian Gulf. The scenario proposed buys time to build the vast infrastructure needed for solar and/or hydrogen-fired water distillation. Finally, brine chemicals and deuterium (possibly for fusion energy) will be valuable by-products of distillation, just as with electrolytic hydrogen production.

IV. On the Role of Non-renewables and Nuclear Energy, during the Transition Period

A transition period between decades and over a century is expected. At its end the main fuels will be presumably hydrogen, ammonia, and methane produced to a considerable extent from coal and hydrogen. Consumers will use more and more electricity based on renewables and hydrogen. Some energy will be provided by all traditional fuels and methods, from waste and biofuels, and from an array of methods proposed as solutions of energy problems at various times but which did not achieve widespread use. Solar energy will no doubt have a large number of niche applications, many quite important. Only time will tell whether they will reach the importance of wind and water (or perhaps exceed them).

Nuclear energy may reach its highest peak and greatest importance in helping to get the hydrogen economy started. The peak may be broadened by its application to provide fresh water etc. However, fissile materials, natural or bred, should probably be considered as exhaustable fossil fuels (non-polluting despite passionate views to the contrary) whose importance will therefore ultimately diminish. Some nuclear plants would presumably be kept in operation to provide isotopes and intense radiation environments, but eventually most aging reactors would be replaced by hydrogen plants.

The detailed course of the transition will surely be full of excitement, agitation, economic struggles and realignments, painful readjustments, lobbying, wise and unwise legislation, international intrigue, and no doubt some wars, revolutions, sabotage and terrorism. The role of unions is likely to be complex, involving a spectrum of actions from turf battles, job protection and obstructive political tactics, to statesmanlike actions in the public interest and a constructive economic role (probably soon evolving to the latter). Individual businesses will have a similarly wide spectrum of attitudes and activities, and can be expected to engage even more in narrowly focussed lobbying and public relations to protect their interests in the status quo or in new developing areas.

The world is now so heterogeneous and complex, so riven by civil strife, population pressure, ethnic, religious, tribal, and inter-national antagonisms, so ravaged by flood, famine, disease, desertification, ignorance and superstition, that irrational actions and policies are frequent. Perhaps chaos and the breakdown of civilization will occur rather than a brave new world running on hydrogen. But the human race is hardy and adaptable, and has proved that it can learn from experience. It should not be written off too quickly, therefore, and a somewhat optimistic view can be adopted without fear of condemnation as wishful thinking.

We now return to possible transition scenarios, despite uncertainties making most attempts at prophesy sheer guesswork. We expect oil to be the first major fuel to be exhausted. Long before then it will have been mostly reserved for less easily substituted uses than fuel, like petrochemicals and lubricants. It may be largely replaced rather early by methane as a transportation fuel, and by solar energy in home heating. The first major new hydrogen beachhead will be industrial applications now using hydrogen derived from methane; the utilities, the hydrogen industry, and the fertilizer industry. The first major transportation impact of hydrogen may be its spread from the space program to aviation [3].

The automotive fuel situation will likely be confusing and competitive, and long remain so. Methane will fight ammonia, internal combustion engines will compete with electric cars, and within that class, batteries will fight fuel cells. As hydrogen becomes cheaper and natural gas more expensive, more and more of the former will simply be mixed with the latter. Phasing out hydrocarbons may be delayed by hydrogen, but it is hard to guess for how long. On the one hand heavy oils, oil shales, tar sands and coal are a vast resource upgradable with hydrogen, and their use requires infrastructure orders of magnitude less expensive than that required to "go all the way" with hydrogen. On the other hand environmental concerns, coupled with the argument that the hydrogen route is inevitable anyway, may reduce the strength of that consideration. Pressure to do both is provided by the felt need for energy independence of the industrialized countries. As noted in II, there may be counterpressure by the oil-rich countries to do neither. In the 1970's a large deliberate drop in oil prices, coupled with friendly, instead of belligerent statements by OPEC, doubtless contributed to the demise of the synfuel program. This tactic is less likely to be relevant to hydrogen, as oil will be scarcer when hydrogen has become cheaper and more plentiful. The oil countries are well advised to seek peace and stability and to use their current incomes to diversify away from too prolonged reliance on what will be a dwindling resource, whose monopoly status will be continuously undermined by increasingly competitive alternatives.

V. On Financing the Transition to the Hydrogen Economy

Many mechanisms and sources of capital will doubtless be found to meet the vast requirements of building the hydrogen energy economy. Every effort should be made to sequence the investments to allow them to pay for themselves, achieve synergies, and to enhance opportunities for further investment. Projects can be national, international, investor-owned, owned by governments, by quasi-public consortia, industrial organizations or even individuals. The vast pension trust funds may be imporant sources of financing. Care should be given to avoiding both bureaucratic, administrative, ideological and legal straitjackets and the environmental horrors or other bad consequence of rapid industrial development. Industry, rather than government financing may predominate in the U.S.A., the opposite may be the case in Scandinavia and many other countries. Antarctic wind generators would probably require both international treaties and multi-government funding, though international industrial consortia are certainly not excluded. To concretize these ideas, consider the specific case mentioned earlier, namely, cooperation between electrical utilities and the fertilizer industry.

Utilities need base and peaking power, and reduced generation of pollutants and carbon dioxide. Ammonia manufacture needs them too, but with little peaking power, and hydrogen is the major feedstock. Using wind-power (or other renewables) to generate hydrogen, that feedstock becomes available to the ammonia manufacturer, and a non-polluting fuel is provided to the utility. Besides conventional financing methods, tax-exempt bonds can be justified on pollution-reduction grounds, and both enterprises can reap valuable pollution abatement credits. Depreciation is an important internal source of financing. If used for replacing the old type of equipment by hydrogen infrastructure, additional tax incentives, like extra depreciation or tax credits, can be provided to encourage more rapid changeover to hydrogen and more willingness to anticipate future power requirements rather than merely react to shortages.

Positive effects of synergies and hydrogen cogeneration are significant. Hydrogen production can be done with off-peak power, making ammonia producers and utilities inherent allies. The convenience of on-site hydrogen production may justify building large wind turbines on the ammonia producer's property, which would provide base-load (and peaking) power to the utility, generating most hydrogen with the off-peak power. The ammonia producers may become hydrogen suppliers along with the utilities.

The existing hydrogen industry is in a completely analogous situation, vis-a-vis the utilities, as the ammonia industry is. To the extent that hydrogen and ammonia compete as fuels, the two industries may compete, but joint hydrogen production may make economic sense anyhow. Carefully supervised relaxation of anti-trust laws, as far as hydrogen is concerned, may be in the public interest.

The metallurgical industry, particularly the extractive part, may ultimately become a very significant part of the total hydrogen picture. The main drive, as discussed earlier, is to reduce pollution. As smelting and refining operations are geographically dispersed, the hydrogen situation is perhaps more like that of a collection of small industries than a single large one. A wide spectrum of hydrogen policies should therefore develope, from completely owned in-house hydrogen production and consumption to purchased hydrogen exclusively. In between will be many cases much like those discussed earlier, except that symbiotic, rather than competitive, aspects are likely to predominate initially.

The petrochemical industry presents such a complex picture that even apparently mutually exclusive scenarios are reasonably probable and may even co-exist. Faced on all sides with threats and opportunities, it is a financial giant and currently both the largest producer and consumer of hydrogen, as well as a very significant producer of natural gas. Cursed for oil spills and other affronts to the environment, it is praised by some for substantial efforts toward good environmentalsim. These are dismissed as a public relations ploys by the first group. Substantial steps toward the hydrogen economy can not be so dismissed. They could prolong the life of the industry, as discussed earlier, perhaps indefinitely. Reasonable, or perhaps large hydrogen growth, perhaps funded entirely by the industry, might result. The source of funding is its large cash flow plus the large sums, now spent on exploration, drilling, transportation, beneficiation of sour crudes and other measures to meet increasingly stringent environmental standards, payments to foreign governments, etc. much of which could be redirected to hydrogen. Near total replacement of coal and peat by natural gas or synthetic methane may occur in the next few decades. Existing petrochemical and solid fuel industries, individually or together, will presumably supply it. The financial strength of the former and weakness of the latter suggest near complete acquisition of the solid fuel industry by the petrochemicals, but an important role for large chemical or metals companies can not be excluded.

The outcome of the expected battle between major industries for hydrogen supremacy can not be predicted with confidence. The petrochemical industry has the great advantage of immediate ability to absorb astronomical amounts of hydrogen and vast resources, but the other major players can not be neglected on either count. The influence of foreign investors may become important. The possibility that a new giant, the hydrogen industry and its derivatives, may develope, is real. An eventful chapter of world techno-economic history seems to be taking shape, for which the title "the hydrogen revolution" does not seem out of place.

VI. Conclusion, Questions and Prognostications

This section may seem anti-climatic for many questions and prognostications have already arisen and conclusions reached. But there are points worth discussing further, despite occasional overlap with earlier material.

The strength of popular feeling about the environment must not be minimized. Exaggeration, misinformation, misunderstandings and irrational fears are commonplace, but this must not be allowed to force implementation of expensive measures which are harmful or counterproductive [7]. On the other hand, the opposite fallacy, of denying that problems exist and therefore doing nothing or even opposing needed corrective or preventive action, must be fought resolutely. Good science and technology must combine with realism, common sense, and understanding of the economic implications of what is contemplated in order to arrive at wise courses of action. We believe this can be done with hydrogen, that it should be the darling of religious people, environmentalists, moralists and humanists, blessed by scientists, embraced by technologists, welcomed by philosophers, espoused by industry and forcefully advocated by philanthropists, patriots, pundits and politicians.

We expand on the last sentence. Hydrogen addresses practically all justified environmental concerns simultaneously. It generates no greenhouse gases, no uncontrollable emanations of noxious substances causing cancer, attacking eyes, lungs or other organs, killing trees or other non-human creatures, acidifying lakes, or corroding works of art, architecture or anything else. It leads to no tearing up of the earth, ruining landscapes, polluting air, rivers, streams, or oceans, or to destruction of wild life habitats on land or sea. It needs no dangerous and unsightly power lines or construction of expensive or hazardous pipelines, (though it can use facilities already constructed, of these and other types, with moderate or no modification). It can evolve to where it depends only on renewable sources of energy (wind, water, sun) using any and all non-renewable sources as a temporary (but necessary) means to achieve the transition. When it has reached maturity, it will entail near perfect symbiosis with the rhythms of earth and sun. We will be part of a sustainable global ecology, instead of a mighty destructive force. If this philosophy sinks in, we will have gone a significant distance toward achieving the ideal of One World.

The dreams of idealists are sometimes inconsistent with reality. The hydrogen economy encounters little problem on this score, for every step can be taken in harmony with the physical laws of the universe, as far as we know them. In addition, the evolutionary way in which it will be created ensures the ability to assimilate new knowledge and to reverse steps which turn out to be mistaken. This is how science operates. It should be how we shape our world system.

Problems posed by the hydrogen economy are challenging. The physics of the earth will be essential in the new technology. The interdisciplinary nature of the total effort will rival or exceed what happened in nuclear energy and the space program. As there, chemical engineering will be deeply involved. Organization of the total program will be much looser than those were, being implemented piece-meal by many independent groups. The "conquest" of polar and desert regions and of the ocean, as habitats for humans, is likely to be an important spin-off. The gamut of problems for engineering and applied science will be fascinating, endless, and challenging in almost every phase of the total effort.

Industry will spearhead the effort, and do much on its own. Eventual government and international involvement seems unavoidable (polar wind energy, harnessing ocean currents and others). Much short range R&D, and development of business areas will be done by industry. Many long range R&D projects may need government sponsorship, and, the government(s) will have to be active both in regulating and encouraging the new industry. The analogy with nuclear energy is good here, but government's role should be less pervasive. More could be said on these topics, but it would require additional papers to do them justice.

Those concerned with energy independence have strong motivation to make the transition to hydrogen a reality. In principle any nation can do it. National security will probably dictate that all do. It can be done on a scale appropriate to any size economy. Third world countries may even reap a small benefit from undervelopment; they have less infrastructure to replace and less powerful status quo interests to oppose it.

Will statesmen, politicians, opinion molders and so on push for the hydrogen economy or oppose it? The majority probably will be for it. The case will likely convince most citizens and energize environmentalists. They are strong, growing, organized and vocal. With such broad support, the hydrogen push is likely to be unstoppable. Politicians will soon perceive this and rush to take leadership positions. The inevitability of hydrogen, believed already by many, is coming closer to being fact. The question is how long will inertia, ignorance, greed, tunnel vision and mistaken or narrow national interests hold it up?

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