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Why Hydrogen? The Grand Picture

There are two prime sources of energy to be harnessed and expended to do work. One is the capital energy-saving and storage account; the other is the energy-income account. The fossil fuels took multimillions of years of complex reduction and conservation, progressing from vegetational impoundment of sun radiation by photosynthesis to deep-well storage of the energy concentrated below the earth's surface. There is a vast overabundance of income energy at more places around the world, at more times to produce billionsfold the energy now employed by man, if he only knew how to store it when it is available, for use when it was not available. There are gargantuan energy-income sources available which do not stay the processes of nature's own conservation of energy within the earth's crust "against a rainy day." These are in water, tidal, wind, and desert-impinging sun radiation power. The exploiters of the fossil fuels, coal and oil, say it costs less to produce and burn the savings account. This is analogous to saying it takes less effort to rob a bank than to do the work which the money deposited in the bank represents. The question is cost to whom? To our great-great-grandchildren who will have no fossil fuels to turn the machines? I find that the ignorant acceptance by world society's presently deputized leaders of the momentarily expedient and the lack of constructive, long-distance thinking—let alone comprehensive thinking—would render dubious the case for humanity's earthian future could we not recognize plausible overriding trends.

—R. Buckminster Fuller, 1969[1]

The big powers are seriously trying to find alternatives to oil by seeking to draw energy from the sun or water. We hope to God they will not succeed quickly because our position in that case will be painful.

—Sheikh Ahmad Zaki Yamani, oil minister of Saudi Arabia, 1976[2]

Hydrogen as fuel? It's still Buck Rogers stuff.

—Energy expert, Bonn, February 1980

Ballard Power and United Technologies are leading pioneers in developing fuel cells that are so clean. Their only exhaust is distilled water. Right now, Ballard is working with Chrysler, Mercedes-Benz and Toyota to introduce fuel cells into new cars.

—President Bill Clinton, 1997[3]

In the twenty-first century hydrogen might become an energy carrier of importance comparable to electricity. This is a very important mid- to long-range research area.

—President's Committee of Advisors on Science and Technology, 1997[4]

Now analysts say that natural gas, lighter still in carbon, may be entering its heyday, and that the day of hydrogen—providing a fuel with no carbon at all, by definition—may at last be about to dawn.

—*New York Times*, 1999[5]

We asked ourselves, is it likely in the next 10 or 15 or 20 years that we will convert to a hydrogen car economy? The answer, we felt, was no.

—Secretary of Energy Steven Chu, 2009[6]

This study shows that FCEVs [Fuel Cell Electric Vehicles] are technologically ready and can be produced at much lower cost for an early commercial market over the next five years. The next logical step is therefore to develop a comprehensive and co-ordinated EU market launch plan study for the deployment of FCEVs and hydrogen infrastructure in Europe.

—2010 McKinsey study[7]

These quotations give some idea as to what this book is all about: hydrogen as a nonpolluting, renewable form of energy. Hydrogen—an invisible, tasteless, colorless gas—is the most abundant element in the universe. It is the fuel of stars and galaxies. Highly reactive, it is essential in innumerable chemical and biological processes. It is an energetic yet (by definition) nonpolluting fuel.[8]

Even before Buckminster Fuller's observations, many people had been calling for the use of nature's "current energy account" (solar power in its various manifestations) as an alternative to robbing the world's energy "savings account" (coal, oil, gas). As Fuller pointed out, the problem has been to a large extent not only how to collect this essentially free energy but how to store it. Tapping into solar energy for purposes other than basic solar heating usually means producing electricity. But electricity has to be consumed the instant it is produced because it is difficult to store in large quantities. Hydrogen, a storable gas, solves that problem.

In past decades, efforts to harness renewable energies were driven partly by idealism but more by concerns about energy security—that is, fears that the world's petroleum resources will eventually dry up and about the increasing vulnerability of the long supply lines from the politically unstable Middle East. But as the twentieth century drew to its close and the twenty-first century arrived, environmental concerns became much stronger, to the point that today they dominate much of the national and global political discourse, driving the world toward renewable, alternative forms of energy. Curbing and eventually doing away with pollution has become a global universal concern. Dying forests in Europe and acid rain everywhere were among the initial calls for the need to curb sulfur, nitrogen oxides, hydrofluorocarbons, perfluorocarbons, particulate emissions, and other pollutants. Today it is clear to almost everyone in the world that the very process of combusting fossil fuels, the interaction of carbon in hydrocarbon fuels with the air's oxygen, and the consequent release into and accumulation in the atmosphere of carbon dioxide and other climate-changing gases far above preindustrial levels is raising the world's temperature—the infamous greenhouse effect—and threatening to play havoc with the world's climate.

The new world standard is becoming zero emissions from cars and buses, industry, ships, and home furnaces, a standard to which industrialized countries and emerging economies are aspiring with varying degrees of intensity and dedication. To the minds of many, taking the carbon out of hydrocarbons and relying on the "hydro" part—hydrogen—as a zero-emission chemical fuel is the obvious, though technically difficult, way to minimize and, it is hoped, eventually eliminate global warming.

The basics of global warming are roughly as follows. Carbon dioxide (CO_2) is produced by the burning of fossil fuels as well as by nature's carbon cycle. (Humans and animals exhale it into the atmosphere as part of their metabolic process; green plants absorb it and turn it into plant matter.) CO_2, methane, and other gases act like a greenhouse in the atmosphere: They let solar radiation through the atmosphere to heat the earth's surface, but they prevent the reradiation of some of that energy back into space, thus trapping heat. Some heat entrapment is good; otherwise we would have never evolved in the first place, or we would freeze to death. But the more greenhouse gases are swirling around the atmosphere, the more heat is trapped. Because of diminishing forests around the world and consequent decreases in global CO_2 absorption, and (more important) because of increasing burning of fossil fuels in our ever-more-energy-demanding industrial machinery, the atmosphere's CO_2 content has been going up steadily and increasingly steeply since the beginning of the Industrial Revolution.

Aside from other fundamental climate cycles stretching over thousands or tens of thousands of years (such as ice ages, believed to be caused in part by changes in sunspots and therefore beyond human ability to influence), the earth's climate has been reasonably stable for 10,000 years or so. But this equilibrium is being upset by human-made carbon emissions. The question is how much. Opinions, basic assumptions about the future course of the climate and the amount of expected heat increase, closely related assumptions about global economic development, and faith in the complex computer models that attempt to forecast climate developments vary widely even among the majority of experts who believe that our planet is facing an unprecedented crisis.[9]

As more heat is being trapped and as temperatures climb all over the world, the mainstream opinion among the climate experts of the United Nations' Intergovernmental Panel on Climate Change predicts widespread and drastic impacts on ecosystems, water resources, food and fiber production, coastlines, and human health: the polar ice caps will melt, sea levels will rise, large stretches of coastline (including some of the world's biggest cities) will be inundated, and scores of islands in the Pacific may disappear. Agricultural patterns are likely to change, with grain-growing belts migrating northward. The middle to high latitudes may become more productive as plants absorb more available CO_2. The agricultural yields of the tropics and the subtropics are expected to decrease.

The December 2009 Copenhagen Climate Summit was widely regarded as disappointing in its outcome, with little real accomplishment. Nevertheless, the Copenhagen Accord's opening paragraph clearly and starkly states the basic problem and what needs to be done:

> We underline that climate change is one of the greatest challenges of our time. We emphasize our strong political will to urgently combat climate change in accordance with the principle of common but differentiated responsibilities and respective capabilities. To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change. We recognize the critical impacts of climate change and the potential impacts of response measures on countries particularly vulnerable to its adverse

effects and stress the need to establish a comprehensive adaptation program including international support.

Ten years earlier, a 1999 study that looked at the generation of ozone in four metropolitan areas (Sacramento, Chicago, St. Louis, and Los Angeles) concluded that a future doubling of global atmospheric CO_2 would likely result in higher daily temperatures, which "dominate the meteorological correlations with high tropospheric ozone concentrations"—in other words, higher temperatures would increase the ozone concentrations.[10] More ozone, in turn, would increase the incidence of premature mortality, hospital admissions for respiratory diseases, and respiratory symptoms, the authors said. But some aspects, especially the relationship between ozone levels and premature mortality, are still subject to ongoing research, one author cautioned. In the case of Los Angeles, doubled CO_2 concentrations were expected to increase the annual average daily maximum temperature from the base case 20.7°C to 24.9°C and the annual average daily minimum from 14.1°C to 18.2°C, the researchers calculated. In Chicago, doubled CO_2 would increase the corresponding maximum from 13.5°C to 19.3°C and the minimum from 3.78°C to 10.0°C. For Los Angeles, a table of anticipated extra health costs for one such warmer future year listed $2.552 billion (in 1990 dollars) for premature mortality, $14.19 million for hospital admissions, and $168,000 for respiratory-symptom-days relative to the same cost categories for a typical recent year. For Chicago, the corresponding numbers were $979 million, $2.38 million, and $28,000.

The other principal form of clean energy, electricity, has two strikes against it. First, it is the minority component in the world's energy production and consumption—chemical energy accounts for almost two-thirds. Second, most electricity is produced by burning fossil fuels—coal, natural gas, and petroleum.

According to the May 2009 edition of the U.S. Energy Department's *International Energy Outlook,* total world "marketed" energy consumption (as opposed to "nonmarketed" energy sources, which the report says continue to play an important role in some developing countries) was 472 quads (quadrillion Btu) and was projected to grow to 552 quads by 2015 and 678 quads in 2030.[11] Most of the growth—73 percent—is projected to occur in countries outside the Organization for Economic Cooperation and Development (OECD), with 15 percent growth in the thirty members of OECD, most of them high-income industrial states. Total electricity production in 2006 was 186.3 quads from all sources (liquids, coal, natural gas, nuclear, and renewables), projected to rise to 231.7 quads in 2015 and 300.3 quads in 2030. Coal was the biggest primary source, with 127.5 quads in 2006, 150.7 quads in 2015, and 190.2 quads in 2030. Oil (renamed "liquids" because it now includes biofuels and liquid fuels produced from natural gas and coal) consumption was 172.4 quads in 2006, expected to rise to 183.3 quads in 2015 and 215.7 quads in 2030. Assuming a low-growth scenario, renewable energy, including hydroelectric power, accounted for only 36.8 quads in 2006, rising to 54.0 quads in 2015 and 74.1 quads in 2030. World nuclear energy consumption stood at 27.8 quads in 2006, rising to 31.9 quads by 2015 and 40.2 quads in 2030. And CO_2 emissions, which amounted to 29 billion metric tons in 2006, are slated to rise to 33.1 billion tons in 2015 and 40.4 billion metric tons in 2030, an increase of 39 percent.

Thus, it is safe to say that in general, we work and play with—and, environmentalists would say, increasingly die from—fossil-fueled chemical energy. Gasoline, diesel fuel, heavy oil, jet-grade kerosene, natural gas, wood, biomass, and coal propel airplanes, cars, trains, and ships; run plants; and heat homes, offices, hospitals, and schools. Hydrogen, also a form of chemical energy, can do all those things, and can do them essentially without polluting.

When burned in an internal-combustion engine (piston, rotary, or gas turbine), hydrogen produces mostly harmless water vapor (plus, admittedly, trace emissions from tiny amounts of engine lubricants that are oxidized in the process, and some polluting nitrogen oxides), meaning that an internal combustion engine, even when operating on hydrogen, is not a zero-emission vehicle.[12] When hydrogen is combusted with atmospheric oxygen in an engine, no CO or CO_2 is emitted, no unburned hydrocarbons, no stench, no smoke, and none of any of the other carbon-bearing, earth-befouling discharges we suffer today.

Hydrogen performs even better in fuel cells: electrochemical engines that electrochemically combine hydrogen and oxygen in a flameless process and produce electricity, heat, and pure, distilled water—the mirror image of electrolysis, in which water is split into hydrogen and oxygen by running a current through it. Unlike internal combustion engines, fuel cells produce no nitrogen oxides at all.[13]

Fuel cells have no moving parts. Nearly silent, they can be as much as two and a half times as efficient as internal combustion engines. As one example, the fuel cell version of a Toyota Highlander SUV has demonstrated three times better fuel economy than its standard gasoline version.[14] Beginning in earnest in the 1980s and 1990s, fuel cells have become widely recognized as a vanguard technology that may launch hydrogen energy on its way to becoming a major environmentally benign, sustainable, renewable component of the world's energy mix for both transportation and stationary applications.

"Hydrogen, H_2, atomic weight 1.00797 . . . is the lightest known substance," reports the *Encyclopedia of Chemistry:*

> The spectroscope shows that it is present in the sun, many stars, and nebulae. Our galaxy . . . plus the stars of the Milky Way is presently considered to have been formed 12 to 15 billion years ago from a rotating mass of hydrogen gas which condensed into stars under gravitational forces. This condensation produced high temperatures, giving rise to the fusion reaction converting hydrogen into helium, as presently occurring in the sun, with the evolution of tremendous amounts of radiant thermal energy plus the formation of the heavier elements. Hydrogen gas has long since escaped from the Earth's lower atmosphere but is still present in the atmosphere of several of the planets. In a combined state, hydrogen comprises 11.19 percent of water and is an essential constituent of all acids, hydrocarbons, and vegetable and animal matter. It is present in most organic compounds.[15]

Hydrogen is used in many industries as a chemical raw material, especially in the production of fertilizer, but also in making dyes, drugs, and plastics. It is used in the treatment of oils and fats, as a fuel for welding, to make gasoline from coal, and to produce methanol. In its supercold liquid form, in combination with liquid oxygen, it is a powerful fuel for the space shuttle and other rockets.

Hydrogen is produced commercially in almost a dozen processes. Most of them involve the extraction of the "hydro" part from hydrocarbons. The most widely used, least costly process is steam reforming, in which natural gas is made to react with steam, releasing hydrogen. Water electrolysis, in which water is broken down into hydrogen and oxygen by running an electrical current through it, is used where electricity is cheap and high purity is required.

Hydrogen can be stored as a high-pressure gas or as an integral component in certain alloys known as hydrides, as so-called chemical hydrides, in and on microscopic carbon fibers, and with other only recently developed sophisticated technologies. As a cryogenic liquid fuel, it promises to lead to better, faster, more efficient, environmentally clean airplane designs. Metallic hydrogen, a laboratory curiosity so far, holds eventual, distant promise as an ultra-energetic fuel and also as a zero-resistance electrical conductor in all sorts of electrical and electronic technologies—if it can be made in sufficient industrial quantities and be made stable at higher, near-ambient temperatures.

Since the 1930s, environment-minded scientists, academics, and energy planners (inside and outside government), industrial executives, and even some farsighted politicians have been thinking of and supporting the concept of hydrogen as an almost ideal chemical fuel, energy carrier, and storage medium. As a fuel, it does not pollute. As an energy-storage medium, it would answer Fuller's call for some method "to store [energy] when it is available for use when it is not available."

Hydrogen is not an energy source, a mistake that otherwise sophisticated, well-informed people still make. That is, it is not primary energy like natural gas or crude oil that exists freely in nature. It is an energy carrier—a secondary form of energy that has to be manufactured like electricity, which does not exist freely in usable form either. One fascinating aspect is the complementarity of hydrogen and electricity, of great relevance to the whole notion of fuel cell cars and electrification of the automobile, something that carmakers are now pursuing intensively. Hydrogen can be converted in a fuel cell to electricity, plus some heat and water, via the electrochemical combination with the air's oxygen. Running in reverse—and some experimental two-way devices have been built—water can be split into hydrogen and oxygen with an electric current in an electrolyzer. The late Geoffrey Ballard, founder of the Canadian fuel cell developer Ballard Power Systems, coined the word *hydricity*, for hydrogen and electricity, around the turn of the century to describe this phenomenon.

Hydrogen can be generated from many primary sources—an advantage in itself, since it reduces the chances of creating a hydrogen cartel similar to OPEC. Today hydrogen is made (that is, extracted) mostly from fossil fuels. But efforts to clean up these fuels (to "decarbonize" them, in the jargon of energy strategists) will increase. "To decarbonize" really means to adapt and improve techniques long used in the chemical, petroleum, and natural gas industries to strip out the carbon or CO_2 and store ("sequester") it out of harm's way, leaving hydrogen.

In the future, hydrogen will be made from clean water and clean solar energy, from biomass and biofuels, even from coal —and possibly from cleaner versions of nuclear energy. Since it can be made from both non-renewable and renewable sources, it can be phased into the overall energy structure by whatever method is most convenient and least wrenching to a given country, state, region, or economy. Possibilities are coal gasification in the western United States and solar-based electrolysis in deserts in the Middle East or the southwestern United States. Israeli scientists are testing direct solar water splitting, in which the sun's concentrated heat would break up water molecules into hydrogen and oxygen. Water could be electrolyzed with electricity produced by geothermal resources in some areas, and perhaps also from the oldest form of renewable energy: hydropower.

In the simplest terms, the broad outlines of a future "hydrogen economy" run something like this. Clean primary energy—probably solar energy in its many variations; possibly an advanced, environmentally more benign version of nuclear energy—would produce electricity, which would be used to split water into hydrogen as fuel, with oxygen as a valuable by-product. Alternatively, heat produced by solar or nuclear power plants would be used to crack water molecules thermochemically in processes now under development. More exotic methods in which hydrogen is produced—from genetically engineered microbes, algae, cellulosics, and other biological processes—are likely candidates further down the road.

Hydrogen would be used as an energy-storage medium—as a gas under pressure in large, depleted natural gas fields perhaps, in hydrogen-absorbing alloys (the above-mentioned hydrides), as a cryogenic liquid, or in activated-carbon materials and carbon nanostructures; but also in the form of relatively conventional fuels, such as methanol, which some regard as a superior fuel to carry hydrogen. Hydrogen could fulfill the indispensable storage function of smoothing the daily and seasonal fluctuations of solar power and other intermittent energy sources.

Hydrogen could be burned in modified internal combustion engines that ordinarily run on fossil fuels—jets, turbines, four-strokes, two-strokes, Wankels, diesels. This was the vision, conviction, and message of hydrogen's supporters from the 1970s through the mid-1990s. Since then, with sudden and rapid advances in fuel cell technology, the emphasis has shifted dramatically toward fuel cells as the future engines of choice for transportation[16] and also as clean, efficient, decentralized sources of electricity for buildings. Ultimately, fuel cells operating on pure hydrogen would be quintessentially clean, producing no nitrogen oxides and no hydrocarbons. The only stuff coming out an exhaust pipe would be harmless water vapor (steam), which returns to nature's cycle of fog, clouds, rain, snow, groundwater, rivers, lakes, and oceans. That water could then be split again for more fuel.

As a gas, hydrogen can transport energy over long distances, in pipelines, as cheaply as electricity (under some circumstances, perhaps even more efficiently), driving fuel cells or other power-generating machinery at the consumer end to make electricity and water.[17]

As a chemical fuel, hydrogen can be used in a much wider range of energy applications than electricity. For example, it is difficult to envision a large commercial airliner powered by electric motors of any conceivable type, but hydrogen is seen as a promising future fuel for aviation (see chapter 8). In addition, hydrogen does double duty as a chemical raw material in a myriad uses. And unlike other chemical fuels, it does not pollute.

Two major goals of international hydrogen research have been to find economical ways of making the fuel and determine how to store it efficiently onboard a space-constrained car, bus, or truck. During the 1970s and the 1980s, much, if not most, of the hydrogen production research was aimed at splitting large volumes of water molecules. This was perceived as the crucial prerequisite to using hydrogen as a fuel. In the 1990s, the emphasis shifted to making hydrogen energy—not necessarily ultra-pure hydrogen—an industrial and commercial reality. Thus, much more attention has been paid to improving the steam reforming of natural gas. For a while, the efforts of some carmakers to use methanol as a hydrogen carrier for fuel cell vehicles represented another example. It had some ecological appeal because methanol, produced industrially from natural gas, can also be made without major impact on the atmosphere ("carbon dioxide neutral" is the catchphrase) from green plants (biomass) that absorb CO_2 in their growth phase.[18] That appeal has not totally faded away. Methanol is still being promoted by some, and making commercial headway, as an energy source for backup power for small fuel cells for handheld electronics and telecommunications. It is also being promoted for transportation. A third approach was exemplified by the U.S. Department of Energy's logistics-driven strategy of developing, in cooperation with major carmakers, onboard fuel processors that would extract hydrogen from gasoline and other fossil fuels, including methanol. That effort has been discontinued, however, largely because of the added complexity of onboard fuel processing—a "chemical factory under the hood" was the slightly derisive phrase.

In past decades, hydrogen advocates believed that a global hydrogen economy would begin to take shape near the end of the twentieth century and that pure hydrogen would be the universal energy carrier by the middle of the twenty-first century. Hydrogen may not completely attain that lofty status—a lot of other clean energy technologies, promoted by a lot of players, have sprung up in the past two decades—but it is certain to play a much larger role in the decades ahead—directly as a fuel for fuel cells and indirectly as an increasingly large component of carbon-based fuels such as methanol and other conventional fuels. Many see it as an increasingly important complement to electricity. Electricity and electrolysis can break water down into hydrogen and oxygen, and hydrogen recombined with oxygen can produce electricity and water again—the hydricity concept already mentioned. Each will be used in areas where it serves best, and for a long time to come, it will have to compete with, and in fact be dependent on, conventional fossil fuels as its source.

What about nuclear power as a primary energy source for the production of hydrogen? The instinctive short answer from most hydrogen supporters and environmentalists probably is that nuclear power's days have come and gone. As one American antinuclear protester (Claire Greensfelder, coordinator of the Berkeley-based group Plutonium Free Future) famously put it in a CNN interview during the December 1997 Kyoto climate negotiations, "Trying to solve climate change with nuclear power is like trying to cure the plague with a dose of cholera." But that wasn't always so. In fact, in the 1970s, many in the hydrogen community counted on atomic energy as a source of cheap power for splitting the water molecule. As a cosmic energy dance combining the elementary force that heats the sun and the other stars and the elementary building block of all matter, the concept had an almost mystical elegance. But while a nuclear fire burning far away in the cosmos is one thing, building a nuclear reactor in a populated area is quite another—or so it seemed to the increasingly powerful antinuclear forces around the world. In the mid-1970s, orders for new nuclear plants began a sharp decline. And then came Three Mile Island (1979) and Chernobyl (1986). It looked as if those two accidents would be the gravestones of the nuclear age. The debate is not over, though. Some long-term energy thinkers, including some with very good environmental credentials, believe that a second wave of environmentally much more acceptable nuclear power stations may well be inevitable and may become a reality in this century. This notion gained traction in the Bush administration and was embraced by the Obama White House as well, although large doubts remain—especially in the wake of the mid-March 2011 tsunami-caused nuclear plant disaster in Fukushima, Japan.

The 1980s were a bad time for environmentalists and clean energy advocates. In the United States, the Reagan administration was basically apathetic to their long-term planetary concerns, focusing instead on military and geopolitical matters. Interest in clean, renewable energy, including hydrogen, did not pick up again until the early 1990s, when worries over environmental issues were mounting. It is probably impossible to give an exact date when that interest got started again, but as good a landmark as any was the publication of Al Gore's 1992 book, *Earth in the Balance: Ecology and the Human Spirit,* augmented by his 2006 documentary, *An Inconvenient Truth.*[19]

For the international community of hydrogen researchers and supporters, a defining moment came in the spring of 1993, when Japan's government announced its WE-NET (World Energy Network) project. This long-range project to help launch hydrogen as the world's clean energy currency of choice was an outgrowth and a redefinition of Project Sunshine, a national multidimensional alternative energy project begun in 1974. The original announcement said that Project Sunshine was to extend until 2020. It would spend the equivalent of about $2 billion on most aspects of hydrogen energy technology—a level of funding and a truly long-term planning horizon, appropriate to the momentous task of addressing a planetary issue such as global warming, that the governments of Western Europe and North America were neither capable of nor particularly interested in at the time. As it turned out, Japan's annual funding for hydrogen was more modest in these early years than expected in the first rush of enthusiasm, both because WE-NET's planners decided to start slowly and cautiously, first analyzing what was needed, and because Japan's once seemingly unshakable economy suffered severe setbacks in the ensuing years. Still, WE-NET was the world's first major hydrogen-centered response by a major industrial country to the growing concerns about global climate deterioration caused by fossil fuels.

Also in the early 1990s, the threat that CO_2 and other trace gases might heat up our planet excessively began to command much more public attention, perhaps faster in Europe and elsewhere than in the United States. Since the 1992 Rio de Janeiro Earth Summit (which many regarded as ineffectual grandstanding), global warming has been reported, discussed, analyzed, dissected, argued, and fought over in countless news stories, interviews, magazines, op-ed pieces, scholarly and popular books, TV programs, and Internet postings.

In the first decade of the twenty-first century, there were still plenty of global warming deniers, in the U.S. Congress notably Senator James Inhofe (R, Oklahoma) and Congressman Dana Rohrabacher (R, California), and there are many other doubters around the world. Supporters of renewable, alternative, carbon-neutral, zero-emission energy technologies say it is better to be safe than sorry. In the decade up to the year 2000, the business-as-usual course was the one much preferred and vigorously lobbied for by the world's traditional energy industries and their allies, documented exhaustively and persuasively by Ross Gelbspan in his book *The Heat Is On* (1997), but since then, evidence has been growing that big oil, coal, and other industries are in the process of changing their minds—if slowly and in fits and starts.[20] Greenhouse gases exist in tiny fractions in the atmosphere—only parts per million and even per billion. A fear is that a minuscule change in concentrations could trigger big, unanticipated, and possibly traumatic change in the atmosphere. As Alan Lloyd, the secretary of the California Environmental Protection Agency under Governor Arnold Schwarzenegger and one of the pivotal figures on the American hydrogen scene since the 1990s, put it in March 1998, addressing a Society of Automotive Engineers fuel cell workshop in Cambridge, Massachusetts, "Environmental pollution will likely represent the 'cold war' of the next century."

If hydrogen's benefits as a fuel are so great, the average person might reasonably ask why it did not make significant inroads into our energy systems years or even decades ago. There is no single, simple answer to that question; there is instead a complex array of interlocking factors. For one, there was no real use for hydrogen as long as there were ample supplies of oil and natural gas and as long as environmental worries were the concerns of a tiny, near-silent minority. Hydrogen's principal advantage over conventional fuels is that it is emission free. That, by itself, was not thought to merit a society-wide switch to alternatives of any sort. Fossil fuels were cheap, and hydrogen was as much as several times more expensive. Liquid hydrogen, the coldly exotic stuff that powers the space shuttle and experimental BMW sedans today, was a laboratory curiosity four or five decades ago.

Technologically the level of development was such that producing, handling, and storing hydrogen was complex, difficult, and perhaps beyond the abilities of the routine consumer. It still is, although it has been improving rapidly and dramatically to the point where hundreds of hydrogen cars are operating on public roads, many of them driven by average everyday drivers, not trained technicians.

Bringing a technology to maturity takes time. David Hart, a consultant and director of the London- and Lausanne-based sustainable energy consultancy E4tech and Principal Research Fellow at Imperial College London, observed in 2000, "We have only recently become able to operate really well with natural gas." He believed the time was finally at hand when hydrogen would start to make major inroads because of "a confluence of drivers that all point in the same direction—towards hydrogen." The drivers include the requirement for a reduction in CO_2 emissions, appalling urban air quality, legislation dictating zero-emission vehicles, progress in fuel cell technology, a move toward the use of local resources for energy production, the need to store intermittent renewable energy, concerns about fossil fuel resources, and the security of energy supplies. Hart concluded: "There is only one common thread running through these, and that is hydrogen. While other energy carriers can assist in achieving some of these objectives, none of them meet all of the requirements. That is why even the major oil companies see hydrogen as a major part of the energy future."[21]

Automobiles have been around for more than 100 years, yet even the best-engineered examples still break down. Perhaps most important, societal issues have prevented major progress. For one, replacing an entire technologically advanced energy system with something else is a huge undertaking, spanning decades. It is like trying to change the course of a supertanker with kayak paddles. Noted one expert in the 1990s, "The energy system consists of an immense infrastructure, enormous physical and human capital, not only tanks and pipelines and motors, but also people—bankers, auto mechanics, drillers, etc. (and politicians, he might have added), hence it evolves slowly." Phasing in hydrogen requires "innumerable replacements"; substituting fuel cells for internal combustion engines is only one small aspect.

Perhaps the biggest impediment to change for the better is our value system—what we are willing to pay for. By and large, environmental health is not high on the list. As one American expert with experience in both the halls of Congress and hands-on alternative energy research, C. E. (Sandy) Thomas, a former Senate energy aide and former president of H2Gen Innovations, a Virginia-based manufacturer of hydrogen production and purification equipment and now a respected consultant and analyst, summarized the issue in 2009 in a note to the author,[22] hydrogen has not taken off because society does not yet place value on sustainability:

> In economic terms, the cost of fuels does not include the externalities of health effects due to urban air pollution, oil spills, ground water contamination, the military cost of defending oil, and, most important, the potential risks of major climate change. Put another way, society has a very high discount rate—we discount any adverse effects that occur in the future.
>
> If the price of coal, oil, and, yes, even natural gas included a full accounting of externalities, then hydrogen would look much more promising overnight. If people had to pay $10/gallon for gasoline or 30 cents/[kilowatt-hour] for electricity to cover fossil fuel damages to our health and environment, then suddenly hydrogen fuel-cell vehicles and hydrogen produced by wind, solar or biomass would look like a bargain. Investors would flock to hydrogen equipment manufacturers. People would convert their SUVs to run on clean-burning hydrogen derived from wind energy at only $2.50/gallon of gasoline equivalent.
>
> A truly sustainable energy future has two attributes: no pollution or greenhouse gas emissions, and no consumption of non-renewable resources. There are only two energy options that meet this sustainability goal: renewable hydrogen and fusion.

Pessimistically, Thomas added:

Sustainability requires the intervention of governments. Governments alone have the responsibility of protecting the commons. Industry has no major incentive (other than public relations) to build a sustainable energy system. Their overriding objective is return on investment, and burning fossil fuels is very profitable. At best, they will sponsor renewable energy R&D or fuel-cell programs with an infinitesimally small fraction of their profits to give the appearance of preparing for a sustainable future. But most governments do not have the vision or leadership to look into the future and to implement policies that will provide for the welfare of future generations.

Summarizing, Thomas said:

All the key decisions makers who could influence a transition to clean energy carriers like hydrogen have a very short time horizon: industries have to show a return on investment within a few years, and most elected officials feel that they must show results before the next election—at best six years for a Senator, four years for a President, and only two years for a Representative.

Reflecting on recent events, Thomas added:

We were all hopeful that President Obama would provide the necessary vision and leadership. Unfortunately he has been diverted by two wars, the worst economy since the Great Depression and a domestic agenda dominated by health care reform. As a result, he left the energy debate in the hands of Steven Chu, a Nobel laureate in physics who has the credentials and science background to understand the unique advantages of a transportation future built around hydrogen and fuel cells. Much to our shock and dismay, Dr. Chu zeroed out the hydrogen and fuel cell electric vehicle program as his first action as Secretary of Energy. As best we can determine, he made this short-sighted, devastating decision without consulting with any of the key players including automobile companies that have spent billions of their own dollars developing fuel cell electric vehicles over the last 15 years, the energy companies, or even his own Hydrogen Technical Advisory Committee (HTAC) that was set up to advise the Secretary on the hydrogen program. This action could set the hydrogen economy back another decade or two.

Earlier, he had asked:

Where do we find the visionary leaders who will look two or three decades into the future and imagine a better world for their children, grandchildren or even great grandchildren?

And the costs are changing. Fossil fuels will be harder to find and more expensive, and renewables are definitely getting cheaper. Warned Fatih Birol, the chief economist of the International Energy Agency, in an August 3, 2009, interview with Britain's *The Independent* newspaper, "One day, we will run out of oil, it is not today or tomorrow. . . . We will have to leave oil before it leaves us, and we will have to prepare ourselves for that day." The cost of storage and use technologies such as fuel cells are on a downward trajectory, though they have some way to go. Their advantages are forcing development in the right directions as the costs of conventional fuels are going up. Health and damage costs are much higher than ever before, and people are starting to consider them, though they may not be added to the price of a gallon of diesel.

Fears about global warming and CO_2 buildup in the atmosphere surfaced decades ago. In 1979, for example, a British Broadcasting Corporation TV documentary about hydrogen energy, "The Invisible Flame," quoted a meteorologist stationed in Hawaii, home of one of the world's most important atmospheric CO_2-monitoring posts, as follows: "We don't know at this point whether [CO_2] will build up so that it can do damage. The oil crisis may have slowed it a little. . . . A lot of people believe we could get into trouble, irreversible trouble, in about ten years' time."

Hydrogen contains no carbon at all. Burning it and converting it to energy produces no CO_2 and no greenhouse gas. Used as a fuel, it would reduce and eventually eliminate at least the man-made share of CO_2 deposited in the atmosphere. Switching to hydrogen energy—even using hydrogen from fossil fuels as a bridging measure—may help save our children's health and perhaps their lives; using hydrogen made from natural gas and used in fuel cell vehicles would reduce greenhouse gas emissions by approximately 50 percent right away.

The sky isn't falling—yet. But unless something is done on an international scale, with measures that prove we can actually use our collective human intelligence and wits to guarantee our survival, the time may come when the sky will turn so gray, poisonously yellow, or red from heat and pollution that it might as well be falling. Time will undoubtedly tell.