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Hydrogen futures: toward a sustainable energy system ☆

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Abstract

Fueled by concerns about urban air pollution, energy security, and climate change, the notion of a “hydrogen economy” is moving beyond the realm of scientists and engineers and into the lexicon of political and business leaders. Interest in hydrogen, the simplest and most abundant element in the universe, is also rising due to technical advances in fuel cells — the potential successors to batteries in portable electronics, power plants, and the internal combustion engine. But where will the hydrogen come from? Government and industry, keeping one foot in the hydrocarbon economy, are pursuing an incremental route, using gasoline or methanol as the source of the hydrogen, with the fuel reformed on board vehicles. A cleaner path, deriving hydrogen from natural gas and renewable energy and using the fuel directly on board vehicles, has received significantly less support, in part because the cost of building a hydrogen infrastructure is widely viewed as prohibitively high. Yet a number of recent studies suggest that moving to the direct use of hydrogen may be much cleaner and far less expensive. Just as government played a catalytic role in the creation of the Internet, government will have an essential part in building a hydrogen economy. Research and development, incentives and regulations, and partnerships with industry have sparked isolated initiatives. But stronger public policies and educational efforts are needed to accelerate the process. Choices made today will likely determine which countries and companies seize the enormous political power and economic prizes associated with the hydrogen age now dawning.

1. Introduction

Hermina Morita has a grand vision for Hawaii’s energy future. A state representative, Morita chairs a legislative committee to reduce Hawaii’s dependence on oil, which accounts for 88 percent of its energy and is mainly imported on tankers from Asia and Alaska. In April 2001, the committee approved a $200,000 “jumpstart” grant to support a public/private partnership in hydrogen research and development, tapping the island state’s plentiful geothermal, solar, and wind resources to split water and produce hydrogen for use in fuel cells to power buses and cars, homes and businesses, and military and fishing fleets. The grant grew out of a consultant study suggesting that hydrogen could become widely cost-effective in Hawaii this decade. The University of Hawaii, meanwhile, has received $2 million from the US Department of Defense for a fuel cell project. Possibilities include Hawaii’s becoming a mid-Pacific refueling point, shipping its own hydrogen to Oceania, other states, and Japan. Instead of importing energy, Morita told a San Francisco reporter, “Ultimately what we want...is to be capable of producing more hydrogen than we need, so we can send the excess to California” [1].

Leaders of the tiny South Pacific island of Vanuatu have similar aspirations. In September 2000, President John Bani appealed to international donors and energy experts to help prepare a feasibility study for developing a hydrogen-based renewable energy economy. The economically depressed and climatically vulnerable island, which spends nearly as much money on petroleum-based products as it receives from all of its exports, hopes to become 100 percent renewable-energy-based by 2020. Like Hawaii, it has abundant geothermal and solar energy, which can be used to make hydrogen. And like Hawaii, it hopes to become an exporter, providing energy to neighboring islands.

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"As part of the hydrogen power and renewable energy initiative we will strive to provide electricity to every village in Vanuatu", the government announced [2].

Hawaii and Vanuatu are following the lead of yet another island, Iceland, which amazed the world in 1999 when it announced its intention to become the world's first hydrogen society. Iceland, which spent $185 million — a quarter of its trade deficit — on oil imports in 2000, has joined forces with Shell Hydrogen, DaimlerChrysler, and Norsk Hydro in a multimillion-dollar initiative to convert the island's buses, cars, and boats to hydrogen and fuel cells over the next 30–40 years. Brainchild of a chemist named Bragi Árnason and nicknamed "Professor Hydrogen", the project will begin in the capital of Reykjavík, with the city's bus fleet drawing on hydrogen from a nearby fertilizer plant, and later refilling from a station that produces hydrogen onsite from abundant supplies of geothermal and hydroelectric energy — which furnish 99 percent of Iceland's power. If the project is successful, the island hopes to become a "Kuwait of the North", exporting hydrogen to Europe and other countries. "Iceland is already a world leader in using renewable energy", announced Thorsteinn Sigfússon, chairman of the venture, in March 2001, adding that the bus project "is the first important step towards becoming the world's first hydrogen economy" [3].

Jules Verne would be pleased — though not surprised — to see his vision of a planet powered by hydrogen unfolding in this way. After all, it was in an 1874 book titled *The Mysterious Island* that Verne first sketched a world in which water, and the hydrogen that, along with oxygen, composed it, would be "the coal of the future". A century and a quarter later, the idea of using hydrogen — the simplest, lightest, and most abundant element in the universe — as a primary form of energy is beginning to move from the pages of science fiction and into the speeches of industry executives. "Greenery, innovation, and market forces are shaping the future of our industry and propelling us inexorably toward hydrogen energy", Texaco executive Frank Ingriselli explained to members of the Science Committee of the US House of Representatives in April 2001. "Those who don't pursue it, will rue it" [4].

Indeed, several converging forces explain this renewed interest in hydrogen. Technological advances and the advent of greater competition in the energy industry are part of the equation. But equally important motivations for exploring hydrogen are the energy-related problems of energy security, air pollution, and climate change — problems that are collectively calling into question the fundamental sustainability of the current energy system. These factors reveal why islands, stationed on the front lines of vulnerability to high oil prices and climate change, are in the vanguard of the hydrogen transition [5].

Yet Iceland and other nations represent just the bare beginning in terms of the changes that lie ahead in the energy world. The commercial implications of a transition to hydrogen as the world's major energy currency will be staggering, putting the $2 trillion energy industry through its greatest tumult since the early days of Standard Oil and Rockefeller. Over 100 companies are aiming to commercialize fuel cells for a broad range of applications, from cell phones, laptop computers, and soda machines, to homes, offices, and factories, to vehicles of all kinds. Hydrogen is also being researched for direct use in cars and planes. Fuel and auto companies are spending between $500 million and $1 billion annually on hydrogen. Leading energy suppliers are creating hydrogen divisions, while major carmakers are pouring billions of dollars into a race to put the first fuel cell vehicles on the market between 2003 and 2005. In California, 23 auto, fuel, and fuel cell companies and seven government agencies are partnering to fuel and test drive 70 cars and buses over the next few years. Hydrogen and fuel cell companies have captured the attention of venture capital firms and investment banks anxious to get into the hot new space known as "ET", or energy technology [6].

The geopolitical implications of hydrogen are enormous as well. Coal fueled the 18th- and 19th-century rise of Great Britain and modern Germany; in the 20th century, oil laid the foundation for the United States' unprecedented economic and military power. Today's US superpower status, in turn, may eventually be eclipsed by countries that harness hydrogen as aggressively as the United States tapped oil a century ago. Countries that focus their efforts on producing oil until the resource is gone will be left behind in the rush for tomorrow's prize. As Don Huberts, CEO of Shell Hydrogen, has noted: "The Stone Age did not end because we ran out of stones, and the oil age will not end because we run out of oil." Access to geographically concentrated petroleum has also influenced world wars, the 1991 Gulf War, and relations between and among western economies, the Middle East, and the developing world. Shifting to the plentiful, more dispersed hydrogen could alter the power balances among energy-producing and energy-consuming nations, possibly turning today's importers into tomorrow's exporters [7].

The most important consequence of a hydrogen economy may be the replacement of the 20th-century "hydrocarbon society" with something far better. Twentieth-century humans used 10 times as much energy their ancestors had in the 1000 years preceding 1900. This increase was enabled primarily by fossil fuels, which account for 90 percent of energy worldwide. Global energy consumption is projected to rise by close to 60 percent over the next 20 years. Use of coal and oil are projected to increase by approximately 30 and 40 percent, respectively [8].

Most of the future growth in energy is expected to take place in transportation, where motorization continues to rise and where petroleum is the dominant fuel, accounting for 95 percent of the total. Failure to develop alternatives to oil would heighten growing reliance on oil imports, raising the risk of political and military conflict and economic disruption. In industrial nations, the share of imports in overall oil demand would rise from roughly 56 percent today to 72 percent by 2010. Coal, meanwhile, is projected to maintain its grip on more than half the world's power supply. Continued rises in coal and oil use would exacerbate urban air problems in industrialized cities that still exceed air pollution health standards and in megacities such as Delhi, Beijing, and Mexico City — which experience thousands of pollution-related deaths each year. And prolonging petroleum and coal reliance in transportation and electricity would increase annual global carbon emissions from 6.1 to 9.8 billion tons by 2020, accelerating climate change and the associated impacts of sea level rise, coastal flooding, and loss of small islands; extreme weather events; reduced agricultural productivity and water availability; and the loss of biodiversity [9].

Hydrogen cannot, on its own, entirely solve each of these complex problems, which are affected not only by fuel supply but also by factors such as population, over- and under-consumption, sprawl, congestion, and vehicle dependence. But hydrogen could provide a major hedge against these risks. By enabling the spread of appliances, more decentralized "micropower" plants, and vehicles based on efficient fuel cells, whose only byproduct is water, hydrogen would dramatically cut emissions of particulates, carbon monoxide, sulfur and nitrogen oxides, and other local air pollutants. By providing a secure and abundant domestic supply of fuel, hydrogen would significantly reduce oil import requirements, providing the energy independence and security that many nations crave [10].

Hydrogen would, in addition, facilitate the transition from limited non-renewable stocks of fossil fuels to unlimited flows of renewable sources, playing an essential role in the "decarbonization" of the global energy system needed to avoid the most severe effects of climate change. According to the World Energy Assessment, released in 2000 by several UN agencies and the World Energy Council, which emphasizes "the strategic importance of hydrogen as an energy carrier", the accelerated replacement of oil and other fossil fuels with hydrogen could help achieve "deep reductions" in carbon emissions and avoid a doubling of pre-industrial carbon dioxide (CO_2) concentrations in the atmosphere — a level at which scientists expect major, and potentially irreversible, ecological and economic disruptions. Hydrogen fuel cells could also help address global energy inequities — providing fuel and power and spurring employment and exports in the rural regions of the developing world, where nearly 2 billion people lack access to modern energy services [11].

Despite these potential benefits, and despite early movements toward a hydrogen economy, its full realization faces an array of technical and economic obstacles. Hydrogen has yet to be piped into the mainstream of the energy policies and strategies of governments and businesses, which tend to aim at preserving the hydrocarbon-based status quo — with the proposed US energy policy, and its emphasis on expanding fossil fuel production, serving as the most recent example of this mindset. In the energy sector's equivalent of US political campaign finance, market structures have long been tilted toward fossil fuel production. Subsidies to these energy sources — in the form of direct supports and the "external" costs of pollution — are estimated at roughly \$300 billion annually [12].

The perverse signals in today's energy market, which lead to artificially low fossil fuel prices and encourage the production and use of those fuels, make it difficult for hydrogen and fuel cells — whose production, delivery, and storage costs are improving but look high under such circumstances — to compete with the entrenched gasoline-run internal combustion engines (ICEs) and coal-fired power plants. This skewed market could push the broad availability of fuel cell vehicles and power plants a decade or more into the future. Unless the antiquated rules of the energy economy — aimed at keeping hydrocarbon production cheap by shifting the cost to consumers and the environment — are reformed, hydrogen will be slow to make major inroads [12].

One of the most significant obstacles to realizing the full promise of hydrogen is the prevailing perception that a full-fledged hydrogen infrastructure — the system for producing, storing, and delivering the gas — would immediately cost hundreds of billions of dollars to build, far more than a system based on liquid fuels such as gasoline or methanol. As a result, auto and energy companies are investing millions of dollars in the development of reformer and vehicle technologies that would derive and use hydrogen from these liquids, keeping the current petroleum-based infrastructure intact [13].

This incremental path — continuing to rely on the dirtier, less secure fossil fuels as a bridge to the new energy system — represents a costly wrong turn, both financially and environmentally. Should manufacturers "lock in" to mass-producing inferior fuel cell vehicles just as a hydrogen infrastructure approaches viability, trillions of dollars worth of assets could be wasted. Furthermore, by perpetuating petroleum consumption and import dependence and the excess emission of air pollutants and greenhouse gases, this route would deprive society of numerous benefits. Some 99 percent of the hydrogen produced today comes from fossil fuels. Over the long run, this proportion needs to be shifted toward renewable sources, not maintained, for hydrogen production to be sustainable [14].

In the past several years, a number of scientists have openly challenged the conventional wisdom of the incremental path. Their research suggests that the direct use of hydrogen is in fact the quickest and least costly route — for the consumer and the environment — toward a hydrogen infrastructure. Their studies point to an alternative pathway that would initially use the existing infrastructure for natural gas — the cleanest fossil fuel, and the fastest growing in terms of use — and employ fuel cells in niche applications to bring down their costs to competitive levels, spurring added hydrogen infrastructure investment. As the costs of producing hydrogen from renewable energy fell, meanwhile, hydrogen would evolve into the major source of storage for the limitless but intermittent flows of the Sun, wind, tides, and Earth's heat. The end result would be a clean, natural hydrogen cycle, with renewable energy used to split water into oxygen and hydrogen, with the latter used in fuel cells to produce electricity and water — which then would be available to repeat the process [15].

There are no major technical obstacles to the alternative path to hydrogen. As one researcher has put it, "If we really decided that we wanted a clean hydrogen economy, we could have it by 2010". But the political and institutional barriers are formidable. Both government and industry have devoted far more resources to the gasoline- and methanol-based route than to the direct hydrogen path. Hydrogen receives a fraction of the research funding that is allocated to coal, oil, nuclear, and other mature, commercial energy sources. Within energy companies, the hydrocarbon side of the business argues that oil will be dominant for decades to come, even as other divisions prepare for its successor. And very little has been done to educate people about the properties and safety of hydrogen, even though public acceptance, or lack thereof, will in the end make or break the hydrogen future [16].

The societal and environmental advantages of the cleaner, more secure path to hydrogen point to an essential — and little recognized — role for government. Indeed, without aggressive energy and environmental policies, the hydrogen economy is likely to emerge along the more incremental path, and at a pace that is inadequate for dealing with the range of challenges posed by the incumbent energy system. Neither market forces nor government fiat will, in isolation, move us down the more direct, more difficult route. The challenge is for government to guide the transition, setting the rules of the game and working with industry and society toward the preferable hydrogen future [17].

This catalytic leadership role would be analogous to that played by government in launching another infrastructure in the early years of the Cold War. Recognizing the strategic importance of having its networks of information more decentralized and less vulnerable to attack, the US government engaged in critical research, incentives, and public/private collaboration toward development of what we now call the Internet. An equally, and arguably even more, compelling case can be made for strategically laying the groundwork for a hydrogen energy infrastructure that best limits vulnerability to air pollution, energy insecurity, and climate change. Investments made today will heavily influence how, and how fast, the hydrogen economy emerges in coming decades. As with creating the Internet, putting a man on the moon, and other great human endeavors, it is the cost of inaction that should most occupy the minds of our leaders now, at the dawn of the hydrogen age [18].

2. Gases rising

The fact that a hydrogen economy is inevitably on its way can seem implausible today, at the peak of the oil age. ExxonMobil, BP, Shell, Texaco, and other oil and gas multinationals regularly appear near or at the top of the list of the Fortune's Global 500, pulling in record revenues. Former oil industry executives hold prominent political positions in nations around the world. World oil use is at a record high, with some 3.5 billion tons consumed in 1999. Rising and falling oil prices, decisions by the Organisation of Petroleum-Exporting Countries (OPEC) to cut or raise output, and debates over oil exploration in ecologically sensitive regions often grab headlines [19].

But the reality of an eventual transition to hydrogen becomes more evident when one takes an atomic view of energy history. Since the mid-19th century, the world has been slowly shifting from one form of energy to another — from solids to liquids to gases, as Robert Hefner of the GHK Company has illustrated (see Fig. 1) [20].

Until the middle of the 19th century, reliance on wood for energy was common in most settled parts of the world. But in Great Britain, where population density and energy use were growing rapidly, wood began to lose out to coal, an energy source that was as abundant as wood but more concentrated, and not as bulky or awkward to transport. Coal remained king of the energy world for the remainder of the 19th century and well into the 20th. But by 1900 the advantages of an energy system based on fluids, rather than solids, began to emerge as the transportation system started to shift away from railroads and toward automobiles. This shift created problems for coal, with its weight and volume, at the same time that it generated opportunities for oil, which featured a higher energy density and an ability to flow through pipelines and into tanks. By mid-century, oil had become the world's leading energy source [21].

But dominant as oil is, the liquid now faces an up-and-coming challenger — a gas. Despite improvements from wellhead to gasoline pump, the distribution of oil is rather cumbersome. Natural gas, in addition to being cleaner and lighter and burning more efficiently, can be distributed through a network of pipes that is less conspicuous, more efficient, and more extensive than the one used for oil. As far as use is concerned, natural gas is now the fastest-growing fossil fuel, the fuel of choice for electricity, and the second-leading energy source, overtaking coal in 1999 [21].

The move from solid to liquid to gas fuels involves another sort of transition: the less visible process of "decarbonization". From wood to coal to oil to natural gas, the ratio of hydrogen (H) to carbon (C) in the molecule of each successive source has increased. Roughly speaking, the ratio is between 1–3 and 1–10 for wood; 1–2 for coal; 2–1 for oil; and 4–1 for natural gas (see Fig. 2). Between 1860 and 1990, the H–C ratio rose sixfold (see Fig. 3). Jesse Ausubel of Rockefeller University argues that "the most important,

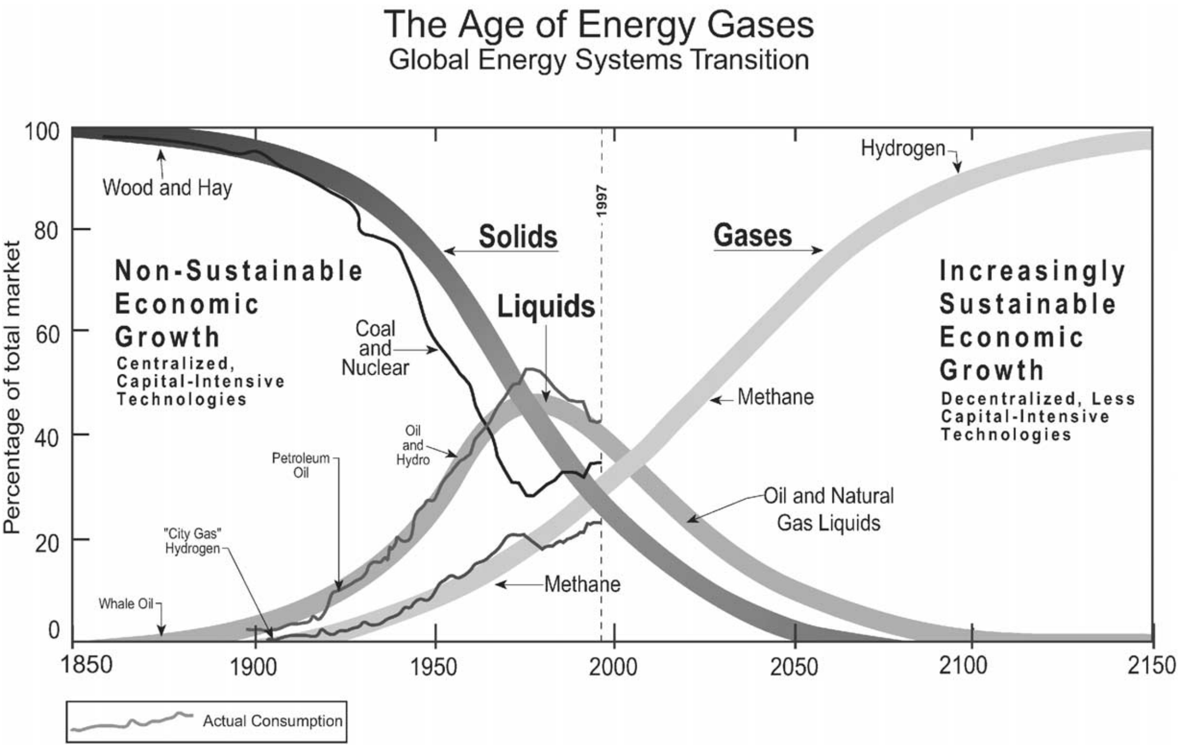

Fig. 1. Global energy systems transition, 1850–2150. Source: see [20].

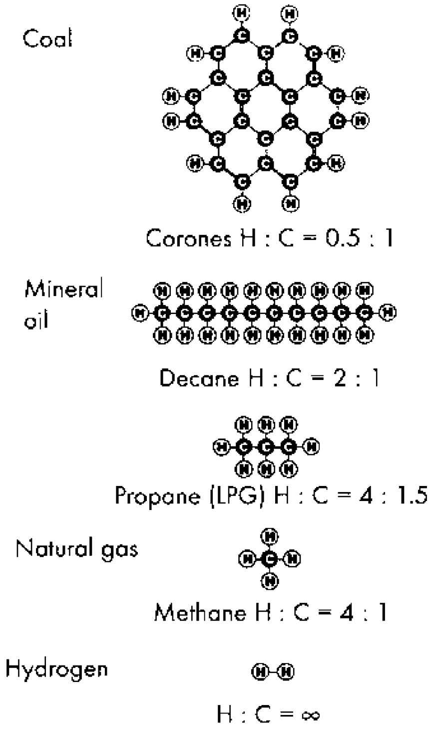

Fig. 2. The atomic hydrogen/carbon ratio. Source: see [22].

surprising, and happy fact to emerge from energy studies is that for the last 200 years, the world has progressively favored hydrogen atoms over carbon… . The trend toward ‘decarbonization’ is at the heart of understanding the evolution of the energy system” [22].

The next logical fuel in this progression is hydrogen, the lightest and most abundant element in the universe and the power source of our Sun. Found on Earth in water, life forms, and hydrocarbon fuels, hydrogen is already established in space programs and industrial applications, thanks to ongoing improvements in the fuel cell. The emergence of hydrogen as a major energy carrier could initially build on the existing natural gas network for its distribution, with the hydrogen derived at first from natural gas to run high-efficiency fuel cells. Eventually, hydrogen will likely use its own full-fledged network, created by splitting water into hydrogen and oxygen using electricity from solar, wind, and other forms of renewable energy. The production of hydrogen from virtually limitless stores of renewable sources will free the energy system from carbon [17].

One of the basic elements of nature, hydrogen is the universe’s simplest element, with each atom composed of just one proton and one electron. It is the most abundant element as well, accounting for more than 90 percent of the observable universe. More than 30 percent of the mass of the Sun is atomic hydrogen [17].

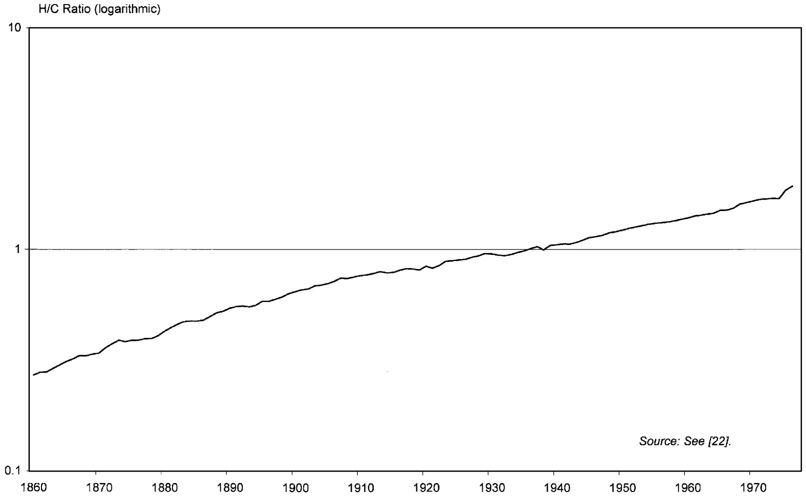

Fig. 3. Hydrogen–carbon ratio, world energy mix, 1860–1990.

The discovery of hydrogen gas emerged from the doubts of scientists and philosophers that water and oxygen were basic elements. It was first identified by the British scientist Henry Cavendish, who proved to the Royal Society of London in 1766 that there were different types of air: “fixed air”, or carbon dioxide, and “flammable air”, or hydrogen. He also demonstrated that hydrogen was much lighter than air and was the first to produce water from hydrogen and oxygen with the help of an electric spark [23].

The French chemist Antoine Laurent Lavoisier repeated Cavendish’s experiments, and after several attempts succeeded in combining hydrogen and oxygen to produce water. His 1785 experiments, performed before numerous scientists, were considered definitive in proving that hydrogen and oxygen were the basic elements of water. Lavoisier was the first to assign these names to the two elements [23].

During the 19th century, the characteristics and potential uses of hydrogen were discussed by clergymen, scientists, and writers of science fiction. In one of the most well-known examples, an engineer in Jules Verne’s 1874 novel The Mysterious Island informs his colleagues, “Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.... Water will be the coal of the future” [23].

As journalist Peter Hoffmann documents in his new book, *Tomorrow’s Energy*: *Fuel Cells*, *Hydrogen*, *and the Prospects for a Cleaner Planet*, interest in hydrogen grew in Europe after the First World War, prompted in part by a heightened interest in energy self-sufficiency. The young Scottish scientist J.B.S. Haldane advocated the derivation of hydrogen from wind power through the splitting of water. The German engineer Rudolf Erren converted trucks, buses, submarines, and internal combustion engines to hydrogen, capitalizing on Nazi Germany’s desire for energy self-sufficiency. The Second World War, with new fuel demands and risks of supply cutoffs, led Australia’s Queensland government to consider industrial hydrogen, until the Allied victory made cheap oil and gasoline available again. The US military also explored hydrogen use for its air force, army, and navy during the war — efforts that would lead to the use of liquid hydrogen in the US space program [23,24].

The 1950s saw development of another means of using hydrogen in space applications: a fuel cell that combined hydrogen and oxygen to produce electricity and water. In the 1960s, several scientists proposed the use of solar energy to split water into hydrogen and oxygen, and to later recombine them in fuel cells. The year 1970 marked the first use of the phrase “hydrogen economy”, by General Motors (GM) engineers who foresaw hydrogen as “the fuel for all types of transport” [24].

Scientific interest in hydrogen, led by academics, engineers, and car enthusiasts in California and Michigan, was given a boost by the 1973 oil crisis. Because it suggested that the era of cheap petroleum had ended and that alternatives were needed, the shock led many researchers to advocate the production of hydrogen via electrolysis from presumably safe, clean nuclear power reactors. Governments in the United States, Europe, and Japan began to fund hydrogen research, albeit in sums far smaller than those devoted to syngas and nuclear power. By the early 1980s, many thought the hydrogen economy was “on its way” [24].

In the intervening two decades, oil prices dropped back down to historical lows, causing interest in hydrogen to wane along with support for research. But at the same time, parallel developments — fuel cell technology breakthroughs, debate over the future of oil, concern over the environmental impacts of the energy system — were quietly reviving the notion of a post-fossil-fuel world. These developments represented even greater impetus for change than those in the 1970s had. And the idea of a hydrogen economy had spread from engineers to executives, as illustrated by the firm that had coined the phrase 30 years before, GM. "Our long-term vision", announced Executive Director Robert Purcell to the annual meeting of the National Petrochemical & Refiners Association in May 2000, "is of a hydrogen economy" [24,25].

How fast might the energy system evolve toward hydrogen? Previous energy transitions were driven by growing energy demands, local scarcities, and the continual search for more abundant and accessible energy sources. In the rise of oil and natural gas, local and regional environmental issues have played a relatively limited role. The rate at which hydrogen emerges will also be shaped by growing energy needs, local pressures on conventional resources, and the continuing quest for more plentiful, available fuels; but it will be shaped to a much greater degree by environmental issues as well [21].

The future availability of oil sits at the center of a long-running debate between people representing two schools of thought. In one school, comprised mostly of geologists, the best oil fields have already been discovered — with few new fields since the mid-1970s — and the amount of oil that has yet to be discovered is relatively limited. This group believes that global oil production will reach its peak and mid-depletion point in the near future, perhaps within the decade. In the other school, composed primarily of economists, oil reserves are dynamic, shaped by market demand and technological advances that lower costs and expand the resource base. This group has a rosier outlook for future hydrocarbon use, extending the oil age well beyond the middle of the century. Whichever view is more correct, some countries are not taking their chances. The Emirate of Dubai, which plans to cease relying on oil production after 2013, has recently expressed an interest in hydrogen [26].

Focusing exclusively on the resource base can be misleading, however: the question is whether we will run out of cheap, available oil — prompting us to pursue alternatives. The more salient issue is one of energy security: whether energy will be available in sufficient quantities, and at an affordable price. Because of the uneven geographical distribution of petroleum, the supply of energy could become more unstable as global reliance on imported oil increases. The United States, which consumes 26 percent of the world's oil, imports 51 percent of the oil it uses, a figure projected to reach as high as 70 percent by 2020. In industrial nations overall, the share of imports in overall energy demand is projected to rise from roughly 56 percent today to 76 percent by 2020 (see Table 1). For the Asia-Pacific region as a whole, the share of oil imports in energy requirements is expected to reach 72 percent in 2005, with 92 percent of those imports coming from the Middle East [27].

Table 1
Oil imports as a share of total energy requirements, industrial nations, 1990–2020[a]

Region	1990	2010 (percent)	2020
North America	45	63	63
Europe	53	74	85
Pacific	90	96	96
Total	56	72	76

[a] Source: see [27].

Urban air pollution will be another important stimulus for the hydrogen transition, as gasoline-based vehicles remain important contributors. Many industrial nation cities still exceed ozone and nitrogen dioxide standards. In developing-nation cities, emissions of these pollutants and particulates are much higher. Worldwide, particulate pollution contributes to 500,000 premature deaths annually. Arising from the smog of Los Angeles, a "zero-emission" mandate, requiring carmakers to sell a fixed share of zero- and low-emission cars by 2003, helped spur the 1999 creation of the California Fuel Cell Partnership, which will test 50 cars and 20 buses over the next 2 years. The Global Environment Facility is sharing the costs, with governments and industry, of a $130 million project to deploy 40–50 fuel cell buses in total in major cities with poor air quality in Brazil, Egypt, Mexico, India, and China (likely candidates are São Paolo, Cairo, Mexico City, New Delhi, Beijing, and Shanghai) [28].

A third problem pushing the hydrogen transition is the risk of climate change. Since 1751, the beginning of the industrial revolution, fossil fuel burning has released more than 277 billion tons of carbon to the atmospheric reservoir. The combustion of coal, oil, and natural gas generates annual carbon emissions of more than 6 billion tons (see Fig. 4). This has increased atmospheric carbon dioxide concentrations by 31 percent, from 280 to 369 parts per million (ppm) volume, their highest point in 420,000 years — and possibly in the last 20 million years (see Fig. 5) [29].

It is a well-established fact of planetary science that higher atmospheric levels of greenhouse gases, such as carbon dioxide, raise global surface temperatures. This explains why the surface temperature of Mars, with a thin atmosphere and weak greenhouse effect, is extremely cold while that of Venus, whose atmosphere is thick with carbon dioxide and other heat-trapping gases, is extremely hot. As expected, Earth's surface temperature has been rising with concentrations of carbon dioxide and other greenhouse gases. During the 20th century, global average surface temperature rose by about 0.6°C, with the 1990s the warmest decade and 1998 the warmest year since instrumental record-taking began in 1861 [30].

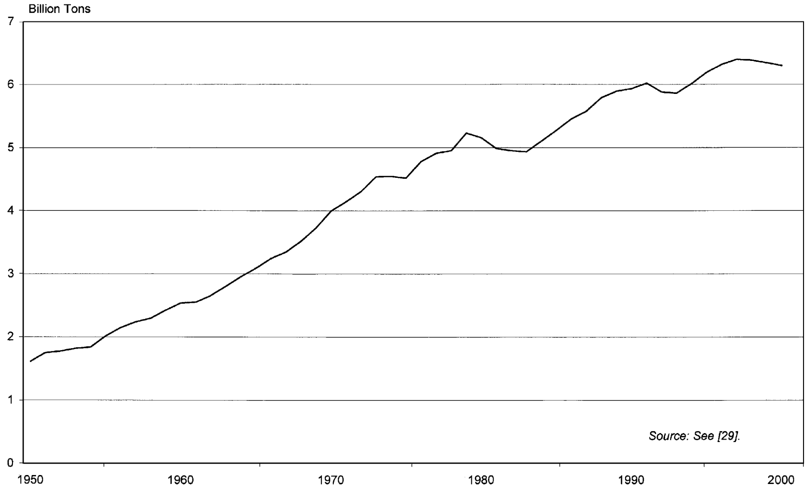

Fig. 4. World carbon emissions from fossil fuel burning, 1950–2000.

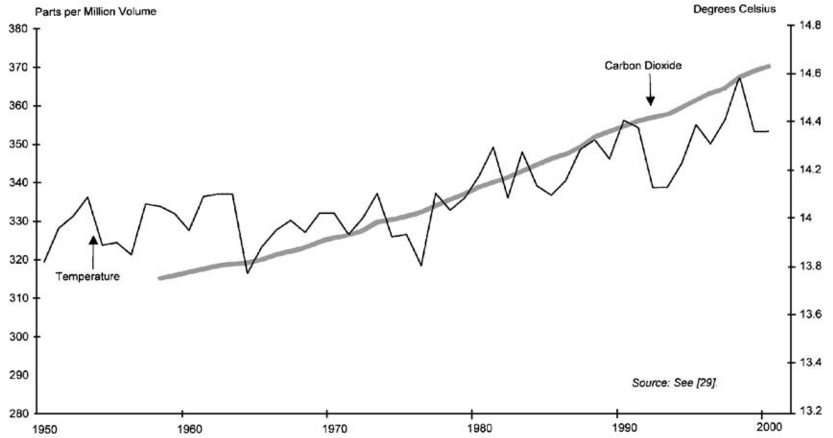

Fig. 5. Atmospheric carbon dioxide concentrations and global average surface temperature, 1950–2000.

Evidence has accumulated of changes in climate, including a 10 percent decrease in snow cover since the late 1960s, a widespread retreat of mountain glaciers in non-polar regions during the past century, and a 40 percent decline in Arctic sea ice thickness between late summer and early autumn. During the 20th century, global average sea level rose between 0.1 and 0.2 m, while precipitation increased by 0.5–1 percent per decade over the Northern Hemisphere. Episodes of the El Niño-Southern Oscillation phenomenon, a periodic warming influenced by the upwelling of Pacific waters, have become more frequent, persistent, and intense since the mid-1970s, as compared with the previous 100 years. Meanwhile, closer study of the temperature record and better modeling have led many scientists to conclude that the warming of the past century, and even that of the last millennium, is highly unusual and unlikely to be entirely due to natural factors. The leading body of climate science, the Intergovernmental Panel on Climate Change (IPCC), stated early in 2001 that “there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities” [30].

The IPCC projects that carbon emissions will be “the dominant influence” on trends in atmospheric CO_2 concentrations during the course of the 21st century. In the panel’s scenarios for the year 2100, CO_2 levels range from 650 to 970 ppm — 90–250 percent above pre-industrial levels. The radiative forcing — or influence — on climate, of all greenhouse gases increases, with the share of CO_2 increasing from one-half to three-quarters [30].

In these scenarios, global average surface temperature rises by 1.4–5.8°C, a rate that is two to nine times as fast as that of the last 100 years, and is probably unprecedented in the last 10,000 years. Global sea level rises by 9–88 cm. Snow cover and sea ice extent continue declining, and glaciers and icecaps continue their worldwide retreat. Precipitation is likely to increase, and weather extremes of drought, heavy rain, and heat waves are expected to become more frequent [30].

A greater frequency of floods and droughts has already been observed, with serious impacts on human populations and economies, though demographic shifts and changes in land use have also played a part. All human and natural systems are sensitive, and some are extremely vulnerable, to changes in climate — agriculture and forestry; coastal zones and fisheries; human settlements; energy and industry; insurance and financial services; and human health. Those populations living in tropical or subtropical climates, small islands, and low-lying coastal zones are least able to adapt and most at risk. Some damage — to glaciers, coral reefs, mangroves, wetlands, and grasslands — will be irreversible and increase the loss of biodiversity. And there is the possibility of "non-linear" effects: the accelerated melting of the West Antarctic Ice Sheet, which could raise sea level by several meters; the slowdown or complete halt of the ocean's heat-carrying circulatory system, which could cause major cooling in northern Europe; and a runaway greenhouse effect through the warming-induced release of carbon from forest dieback and of methane from the thawing of tundra [31].

The panel emphasizes that alternative development paths are possible, and could lead to very different emissions trends. But scenarios leading to lower emissions will depend on a broad range of policy choices, and will require significant policy changes in areas other than climate change. In particular, they will require very different patterns of energy resource development [32].

While carbon emissions will not be limited by the size of fossil fuel resources, the climate constraint suggests that there will need to be a major change in the energy mix and the introduction of new sources of energy during the 21st century. Yet the level at which CO_2 is stabilized will depend on the choice of mix and the investments made now — and most investment today is being channeled toward the discovery and development of more fossil resources [32].

Many technological options exist for responding to climate change, and they continue to broaden. Recent technical progress related to reducing carbon emissions has, according to the IPCC, been significant and "faster than anticipated". Four developments cited by the panel — the successful market growth of wind turbines, the introduction of very efficient hybrid-electric cars, the advancement of fuel cell technology, and the demonstration of underground carbon dioxide storage — relate directly to the hydrogen economy. But without dramatic policy changes, according to the IPCC, energy could remain "dominated by relatively cheap and abundant fossil fuels" [32].

Where economically feasible to transmit, natural gas will play an important role in reducing emissions, in combination with improvements in conversion efficiency and in the greater use of combined-cycle and cogeneration plants that capture and reuse waste heat. Low-carbon supply systems will play an increasingly important role in the longer term, drawing on renewable sources — biomass (based on forestry and agricultural byproducts and municipal and industrial waste), wind, solar, and geothermal, hydro, and ocean energy. Natural gas and renewable energy will benefit from the recent improvement of more decentralized, small-scale "micropower" technologies. These include reciprocating engines, microturbines, Stirling engines, solar photovoltaic (PV) cells, wind turbines, and the fuel cell [32].

The policy portfolio for cutting carbon emissions has four main components. The first is to accelerate the shift toward lower-carbon fossil fuels, from coal and oil to natural gas, by phasing out fossil fuel subsidies, coupling carbon levies with reduced labor and wage taxes, and creating a market for trading carbon domestically and internationally. Another is to improve energy intensity — the energy required per unit of economic output — by enacting incentives and standards to improve the efficiency of power plants, industry, appliances, cars, and buildings, and by encouraging the shift to service economies and less energy-intensive activities. Yet another is to jumpstart renewable energy markets through research and development; tax subsidies for owners; tax incentives and price guarantees for developers; and purchasing requirements for utilities [32].

But the ultimate step in climate stabilization is to facilitate the production and use of pure hydrogen as a carrier of energy. The World Energy Assessment points to "the strategic importance of hydrogen as an energy carrier", particularly because an increasing share of carbon emissions is expected to come from petroleum use for transportation — rising from 47 percent in 1995 to 60 percent in 2100. Having a near-zero-emitting hydrogen energy system, the report concludes, "would provide society with the capacity to achieve, in the longer term, deep reductions in CO_2 emissions...and thereby help make it possible to limit the CO_2 level in the atmosphere to twice the pre-industrial level or less in response to climate change concerns" [11,32].

3. Feedstock today, fuel tomorrow

Hydrogen is everywhere, but it is hard to find on Earth as a separate element. Instead, it is primarily found in combination with oxygen in water, in combination with carbon in a range of hydrocarbon fuels, and in combination with carbon in plants, animals, and other forms of life. Hydrogen bound in water and organic forms accounts for more than 70 percent of the Earth's surface [17].

Once it is extracted, this colorless, odorless, and tasteless element becomes a useful "feedstock", or input, to a variety of industrial activities — and a potentially ubiquitous fuel sufficient to energize virtually all aspects of society, from homes to electric utilities to business and industry to transportation (see Fig. 6). Getting to this point will require economical ways of producing, delivering, storing, and using the hydrogen — ways that are more competitive than the conventional approach with today's fuels. Fortunately, current uses of this gas provide a useful starting point for figuring out the economics of hydrogen [33].

According to the US Department of Energy, approximately 400 billion cubic meters of hydrogen are produced worldwide each year, with about one-fifth of this total coming from the United States. This is roughly equivalent to 360 million tons of oil, or just 10 percent of world oil production in 1999. Most of today's hydrogen is produced at oil refineries or by the chemical industry, largely using steam to reform natural gas. The hydrogen is usually consumed onsite and not sold on the market, and is used predominantly as a feedstock for petroleum refining and for the manufacture of ammonia fertilizer, reins, plastics, solvents, and other industrial commodities. Only about 5 percent of hydrogen is categorized as "merchant" and delivered elsewhere as a liquid or gas by truck or pipeline — though this amount would be enough to fuel a fleet of 2–3 million fuel cell vehicles. Other existing applications for the fuel include the US space shuttle program, which uses liquid hydrogen and oxygen for rocket propulsion and hydrogen-powered fuel cells to provide electricity and water on board. But relatively little hydrogen is currently utilized as an energy source, or as an energy carrier that moves energy from the point of production to the point of use [34].

Steam methane reforming is the most common and least expensive way to produce hydrogen at present. It involves the heating of methane (CH_4), of which natural gas is mostly composed, in a catalytic reactor. This strips away the hydrogen atoms, and steam is then added to the process to free up more hydrogen, with carbon dioxide as a byproduct. Roughly 48 percent of worldwide hydrogen production comes from this fully commercial process. In the United States, 5 percent of natural gas production is reformed to yield hydrogen, mainly for use by the chemical industry. The amount of hydrogen produced is equal to about 1 percent of total US energy use. A number of companies are developing small-scale steam methane reformers to produce hydrogen at local fuel stations, which may prove the most viable near-term hydrogen production option. At a natural gas reforming system in Thousand Palms, California, the hydrogen is estimated to be competitive with current gasoline costs when efficiency gains are taken into account [35].

Pamela Spath and Margaret Mann of the US National Renewable Energy Laboratory (NREL) have examined the environmental consequences of producing hydrogen through catalytic steam reforming of natural gas. Spath and Mann looked at a hydrogen plant that reformed natural gas in a conventional steam reformer, with the resulting gas then purified, and the excess steam resulting from the process used elsewhere. They found that carbon dioxide was the dominant gas, accounting for 98 percent of the total. The CO_2 emitted also accounted for 78 percent of the overall global warming contribution, with the other 22 percent coming from methane emissions, which are lost to the atmosphere during the production and distribution of hydrogen. Operation of the hydrogen plant itself was the source of the majority of the greenhouse gas emissions — 65 percent — with the remaining emissions coming from the plant's construction and from natural gas production and transport. The authors suggest raising the energy efficiency of the process to lower resource use and emissions and improve the overall economics [36].

Coal can also be reformed to produce hydrogen, through gasification. This is a commercial procedure as well, but one that is only competitive with methane reforming where the natural gas is expensive. The size of the world's remaining coal reserves has prompted some scientists to suggest that coal be the main feedstock for hydrogen, which could allow countries like China to move to the fuel sooner. However, this would require that the carbon released by the gasification be sequestered. At the 2000 World Hydrogen Energy Congress in Beijing, Italy and China announced formal plans to cooperate in producing and delivering hydrogen, focusing initially on gasification from coal. India has also been mentioned as a potential site for coal-based hydrogen production [37].

Hydrogen can also be extracted from oil, gasoline, and methanol through reforming. This partial oxidation process, mimicking that of a refinery, is a commercial process as well. But it also requires the use of pure oxygen and, as with coal gasification, is less efficient and emits more carbon dioxide than steam methane reforming. This has led oil producers, too, to become interested in carbon sequestration technologies [37].

Carbon sequestration from hydrogen production involves removing the carbon byproduct from the atmosphere — or from the exhaust gases from a coal gasifier or steam methane reformer — and storing it underground in depleted oil or gas fields, deep coal beds, deep saline aquifers, or the deep ocean. Several energy and electric power companies are aggressively pursuing carbon sequestration, though the technologies are not anticipated to become commercially viable for a decade. In October 2000, BP and Ford donated $20 million to Princeton University to establish a Carbon Mitigation Initiative that will explore the technical and economic viability of this approach [37,38].

Biomass can also be used to produce hydrogen, in two different ways. It can be gasified, like coal, or it can be made through pyrolysis, a process in which the biomass is decomposed by heat to form an oil that is then reformed with steam. Both procedures, however, are relatively sensitive to

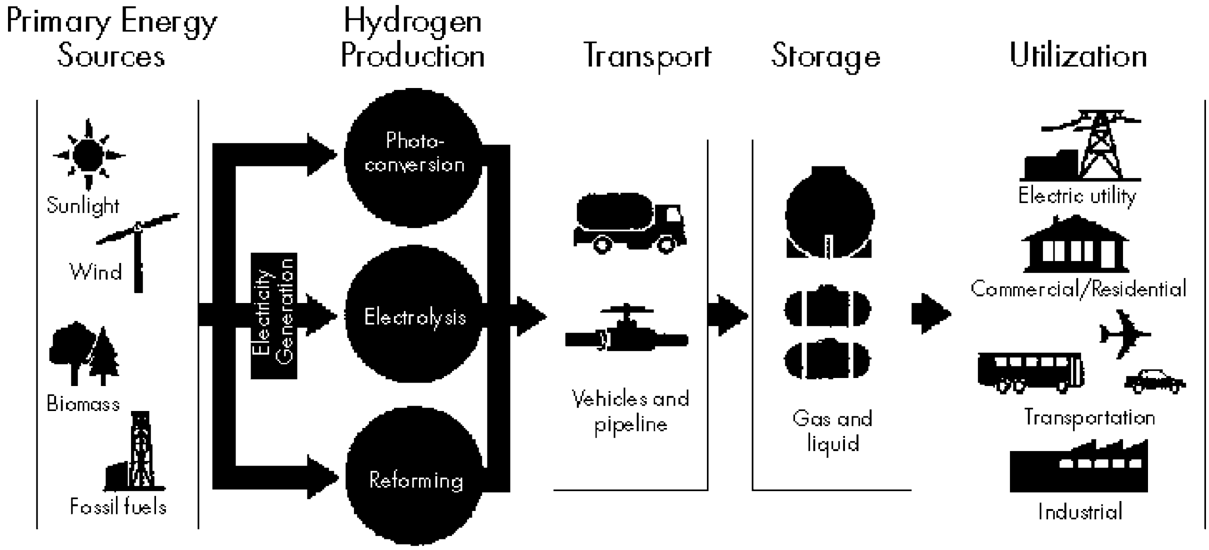

Fig. 6. A hydrogen energy system. Source: see [33].

the price and type of the feedstock and the distance it needs to be transported, although if waste biomass is available the cost of the hydrogen can be competitive. This situation may apply in rural regions of the developing world, where excess biomass is a relatively abundant resource [39].

A promising long-term method of deriving hydrogen is electrolysis, which involves the use of electricity to split water into hydrogen and oxygen atoms. At present, roughly 4 percent of the world's hydrogen is derived from the electrolysis of water. This process is already cost-effective for producing extremely pure hydrogen in small amounts. But electrolysis remains expensive at larger scales, primarily because of the electricity, which currently costs on average three to five times as much as a fossil fuel feedstock. The upfront expense is also an obstacle: in producing hydrogen from a PV system, 85 percent of the price comes from the capital cost of the system [39].

While water electrolysis is the most expensive process of producing hydrogen today, cost declines are expected over the course of the next decade as the technology improves. The costs of PV- and wind-based electrolysis are still high, but are projected to be cut in half over the next decade. In addition, because the hydrogen is produced on site and on demand, the costs of transportation and storage are avoided, which makes electrolyzed hydrogen more competitive with delivered hydrogen. The economics will also improve with future mass production of small electrolyzers that are scalable to small and large units, use less expensive off-peak (and hydroelectric) power, and achieve efficiencies of 70–85 percent [39].

Electrolysis from renewable energy would result in a very clean hydrogen cycle (see Fig. 7). It also represents a potentially enormous source of hydrogen. Hydrogen from solar and wind power could meet projected global energy demand, though the cost of delivering the energy may for some time be higher than that of producing hydrogen from natural gas. Over the past decade, solar and wind-power-based electrolysis systems have been demonstrated in scattered locations in Finland, Germany, Italy,

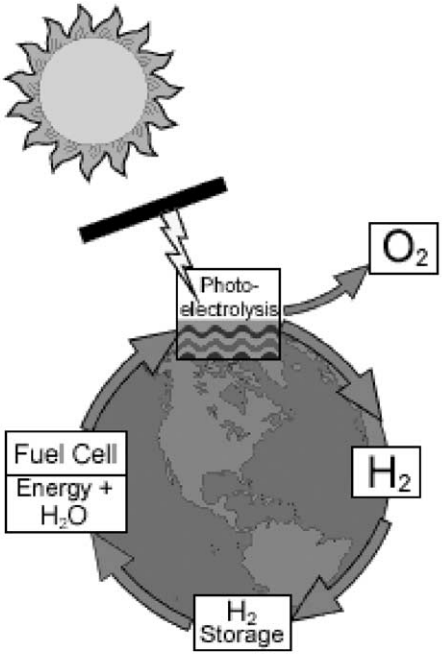

Fig. 7. A renewable hydrogen cycle. Source: see [40].

Saudi Arabia, Spain, Switzerland, and the United States. California's Thousand Palms project, run by the SunLine Transit Agency, has a solar-hydrogen facility operating and a wind-hydrogen facility planned. Feasibility studies have recently been conducted for solar-hydrogen systems in Dubai and several other sun-belt regions, and for wind-hydrogen systems in Northeast Asia [40].

Geothermal power also holds promise for hydrogen production, as Iceland, Vanuatu, and Hawaii seek to demonstrate. Other longer-term options include wave and tidal energy. But areas where cheap hydroelectricity exists — Brazil, Canada, Iceland, Norway, Sweden — may be where renewable electrolysis happens first on a large scale. Canada's BC Hydro and Stuart Energy Systems are constructing a hydropower-to-hydrogen fueling station in Vancouver [41].

"Life cycle" comparisons of the hydrogen production process suggest that electrolysis from renewable energy holds environmental advantages over natural gas reformation, but is still energy-inefficient. NREL's Pamela Spath has found that hydrogen production from wind electrolysis results in greenhouse gas emissions that are one-twelfth those of a large natural gas reformer. However, the overall resource requirements are higher for the wind electrolysis, pointing to the need to improve turbine construction and the efficiency of both the power generation and the electrolysis [42].

Over time, hydrogen will also provide an ideal storage medium for renewable energy. Norsk Hydro is testing out a wind-hydrogen plant in the municipality of Utsira that will produce hydrogen through an electrolyzer and then provide electricity via a fuel cell when the wind is not blowing. Eventually, the hydrogen produced could replace fossil fuels in broader applications, including ferries, which are major contributors to Norwegian air pollution [43].

In some cases, it may be initially more attractive to simply transmit the renewable electricity rather than split and then reproduce water, skipping the hydrogen. The US-based Leighty Foundation, assessing the transmission of wind energy from the Dakota states to Chicago, suggests that it would be more economical today to deliver the energy as electricity than as hydrogen. But if existing pipelines can be used, and improvements in storage and distribution are made, the calculus may change [44].

If electrolysis from renewable energy eventually becomes the primary means of producing hydrogen on a large scale for fueling car fleets, what will be the electricity and land requirements? Paul Kruger of Stanford University suggests that a significant increase in the rate of installing new generating plants will be needed, even with improvements in the efficiency of electrolysis facilities. Provided this happens, he projects that hydrogen-fueled vehicles could almost completely replace the US car fleet by 2050. By one estimate, the fuel needs of the entire US fleet of 200 million could be met by dedicating a small amount of land in the southeast to solar hydrogen. Fourteen percent of the US wind resource that could be developed is also estimated as sufficient to supply hydrogen to the entire national car fleet. Comparable, if not larger, estimates could be made for regions such as equatorial Africa and the Middle East for solar hydrogen, and inland regions of Asia for wind hydrogen. Globally, energy demand in 2050 could be met by solar hydrogen produced on just 0.5 percent of the world's land area [45].

Hydrogen could also serve as part of a grid-independent system using renewable energy, with considerable potential in rural regions where power is lacking or dependent on costly, unreliable diesel generators. The renewable resource would provide power to a remote village or community, with an electrolyzer used to produce hydrogen with the excess power. The hydrogen could then be stored and used to run a fuel cell when more electricity is needed than the renewable source can provide. A stand-alone wind-hydrogen system has been tested in a remote Arctic village [39].

Other methods of using renewable energy to produce hydrogen are being explored. Relatively large solar energy concentrators, such as dish-Stirling engines and power towers, can generate electricity for electrolysis, or supply both heat and electricity to convert steam to both hydrogen and oxygen. Photolysis, the use of direct sunlight on a semiconductor to split water without need of electrolysis, is also being pursued. Biolysis, the use of biological processes, is another possibility. Since most of the hydrogen found in living organisms is created through photosynthesis — which splits water through sunlight — mimicking this process could yield major amounts of hydrogen. By some estimates, it could yield even more hydrogen than solar PV production, due to high expected efficiencies and an abundance of life forms to work with. Anastasios Melis, a chemist at the University of California at Berkeley, is experimenting with producing hydrogen by altering the metabolism of green algae [39,46].

To become a major energy carrier, hydrogen must also be stored and transported in economical fashion — a considerable challenge, owing to the low energy density of the gas. A range of storage technologies that address this problem — compressed gas, liquefied hydrogen, metal hydride, and carbon-based systems — are under development for stationary and onboard vehicle uses (see Table 2). Which choice is best depends on several factors: the application, the energy density needed, the amount to be stored and the time period of storage, the forms of energy available, maintenance requirements, and capital and operating costs [39,47].

Table 2
Methods of storing hydrogen[a]

Method	General use
Underground	Large quantities, long-term storage times
Liquid	Large quantities, long-term storage times
Compressed gas	Small quantities, short-term storage times
Metal hydrides	Small quantities
Carbon nanotubes	Small quantities

[a] Source: see [39,47].

One way to store hydrogen is as a compressed gas, either above or below ground or on board vehicles. With a compressed gas system, the hydrogen is typically compressed and stored in gas cylinders or spherical containers. A number of large-scale hydrogen storage systems have been tried in Europe. In the city of Kiel, Germany, town gas — which is roughly 60 percent hydrogen — has been stored in a gas cavern since 1971. Close to Beynes, France, Gaz de France — the country's national gas company — has stored hydrogen-rich refinery product gases in an aquifer structure. And near Teeside, UK, Imperial Chemical Industries has stored hydrogen in salt mine caverns [48].

For storing hydrogen on board vehicles, compressed hydrogen is the simplest and presently the cheapest method, requiring only a compressor and a pressure vessel. Its main obstacle, however, is its low storage density, which is one-tenth that of gasoline (though this will be partly offset by the higher efficiency of fuel cells relative to internal combustion engines). Higher storage pressures raise the cost, as well as safety issues. Technicians are working on aluminum–carbon and other composite tanks to increase the storage density without creating additional safety problems [48].

As an alternative to compression, hydrogen can be liquefied for storage in stationary or onboard vehicle systems. Liquefaction takes place through a number of steps in which the hydrogen is compressed and cooled to form a dense liquid. The liquid hydrogen must then be stored at very low temperatures, below -250°C. A major drawback for stationary uses of liquid hydrogen is that storage costs are four to five times as high as those for compressed gas, even though transportation costs are much lower. With liquefied hydrogen storage on board vehicles, the main drawback is the high cost of liquefaction and the significant liquid “boil-off” that could occur in the small, insulated containers of parked vehicles. Liquefying hydrogen gas also requires a large amount of electricity — as much as 30 percent of the hydrogen's original fuel energy [48].

A novel means of hydrogen storage is the use of metal hydrides. These are compounds that chemically bond the hydrogen in the interatomic lattice of a metal. The hydrogen is absorbed into the lattice through cooling and released through heating, with the temperature and pressure of these reactions depending on the particular makeup of the hydride. Hydrides are unusual in that they can draw in the hydrogen at or below atmospheric pressure, and release it at higher pressure when heated. Current drawbacks of metal hydrides are that they are heavy, have low densities, require energy to refill, and are comparatively costly. But since the storage costs dominate the overall cost of the hydrogen, very small daily systems — potentially for automobiles — are expected to become cost competitive with other storage technologies [39,48].

Carbon-based systems are another strong hydrogen storage possibility in the early stage of development. Scientists are working to develop materials that can store significant amounts of hydrogen at room temperature — potentially a breakthrough that would enable the practical use of hydrogen-run vehicles. Two types are being explored. Single-walled carbon nanotubes, made up of molecule-sized pores, have achieved an uptake of 5–10 percent, according to researchers at the US National Renewable Energy Laboratory. Graphite nanofibers, stacks of nanocrystals that form a wall of similarly small pores, are being pursued by researchers at Northeastern University who expect to achieve excellent hydrogen storage capacities [39].

Table 3
Methods of transporting hydrogen[a]

Method	General use
Pipeline	Large quantities, long-distance power transmission
Liquid	Large distances
Compressed gas	Small quantities over short distances
Metal hydrides	Short distances

[a] Source: see [48, Table 3].

Chemical hydrides are also being considered for hydrogen storage on board vehicles. Chemicals such as methanol or ammonia could also be used on a seasonal basis in nations like Canada, which has a surplus of hydropower in the summer and a deficit in winter. A chemical carrier has the advantage of an existing transport and storage infrastructure, a commercial technology, and relatively easy liquid and storage handling [39].

The most common way to deliver hydrogen today is with tanker trucks carrying liquid hydrogen, using double-walled insulated tanks to limit the amount of boil-off (see Table 3). Liquid hydrogen can also be transported in metal hydrides, which are loaded onto a truck or railcar. Upon reaching the customer's site, the hydride can be traded for an empty hydride container. Also under consideration are barges or other sea-bound vessels. Canada and Japan have developed ship designs for transatlantic hydrogen transport. However, once the hydrogen is on the ground, trucks may be less effective in distributing hydrogen to decentralized refueling sites [48, Table 3].

Compressed gas can be transported using high-pressure cylinders, tube trailers, and pipelines. In the case of the first two, high-pressure compression is required. The most efficient option for delivering hydrogen gas will be through a network of underground pipelines. These pipelines are similar to those now used for natural gas pipelines, but are adjusted to handle the lower energy density and higher diffusion rate of the hydrogen relative to gas. (Ensuring that new natural gas pipelines can accommodate hydrogen will be an important element in developing the infrastructure.) Pipeline delivery of hydrogen gas already exists in industrial parts of the United States, Canada, and Europe. Germany has been operating a 210 km hydrogen pipeline since 1939. The world's longest hydrogen pipeline to date,

Table 4
Main types of fuel cells[a]

Phosphoric acid
Molten carbonate
Solid oxide
Direct methanol
Alkaline
Proton exchange membrane

[a] Source: see [50].

running from northern France to Belgium, is 400 km long and is owned by Air Liquide. Over 720 km of hydrogen pipeline can be found in the United States, along the Gulf Coast and around the Great Lakes [48, Table 3].

One of the challenges in building hydrogen pipelines is overcoming the high initial expense of installation. One way to accomplish this is to have the cost shared among several suppliers and users, by installing a larger pipeline that can accommodate all of them. This is the approach taken in the US Gulf Coast and Great Lakes [48, Table 3].

4. Engines of change

The final key to the hydrogen energy system is using the fuel economically in internal combustion engines, conventional combustion turbines, and fuel cells. Ongoing research on hydrogen-fueled ICEs is aimed at use in vehicles: BMW launched a “world tour” of its liquid-hydrogen cars in early 2001. Several companies, such as Alstom, Westinghouse, and Mitsubishi, are pursuing the use of hydrogen in gas turbines like those commercially established to run on natural gas [39].

A more likely long-term approach will be to employ hydrogen to run fuel cells. The first scientist to split water into hydrogen and oxygen was also the first to show that the process could be run in reverse. In 1839, the British physicist Sir William Grove demonstrated that hydrogen and oxygen could, through devices known as fuel cells, be electrochemically combined to create water and electricity. But Grove was interested in this process purely for scientific purposes and sought no commercial applications. For over a century, applications of the concept to fuel cells were limited largely to the laboratory. Fuel cells received a boost in the 1960s, when the National Aeronautics and Space Administration used light but expensive models to power the Gemini and Apollo spacecraft [49].

There are six main types of fuel cell, each named according to the electrolyte that is used in the system (see Table 4). The most commercially advanced version, the phosphoric-acid fuel cell (PAFC), has been deployed in several hundred applications around the world. These run generally on either natural gas or propane (others include landfill gas, anaerobic gas, and direct hydrogen) and have been purchased primarily for applications that produce both heat and power. Existing niche markets include landfills, wastewater treatment plants, industrial food processors, high-tech companies, banks, hospitals, and other facilities highly vulnerable to interruptions, as well as “green” facilities that are willing to pay the higher upfront cost to showcase the technology. International Fuel Cells, which has developed fuel cells for the Space Shuttle, has installed more than 200 of its 200–250 kW systems in 15 countries, from a New York City police station to an Alaska postal facility to a Japanese science center. But current PAFC costs range from $4,000 to 5,000-kW — roughly three times the target competitive price — and companies are pursuing alternatives as well [50].

Two types of fuel cells must be operated at high temperatures, above 650°C. These do not require expensive catalysts, and their waste heat can be captured and used to run turbines to increase overall efficiency to 60 percent or more, with the residual heat used for space and water heating. The molten carbonate fuel cell (MCFC) is being pursued by several US and Japanese companies, including Energy Fuel Cell and MC Power Corporation. More than 40 companies worldwide are developing the solid-oxide fuel cell (SOFC), among them Siemens and McDermott [50,51].

Other fuel cells are also being pursued. Alkaline fuel cells, the type used in the Apollo program, are being tested for commercial applications. Direct methanol fuel cells run on methanol without need of a reformer. A researcher at California Institute of Technology is working on a solid acid-based fuel cell whose compounds are relatively easy to manufacture and can function at high temperatures [52].

The fuel cell that is attracting the most attention is the proton exchange membrane (PEM), used in the Gemini mission. This cell's membrane functions as an electrolyte through which protons pass, bonding with oxygen to form water. This leaves the electrons to move along an external circuit, creating an electrical current (see Fig. 8). PEM cells have experienced significant reductions in the cost of producing electrolytes and of creating catalysts that are more resistant to degradation by reformers, which extract the hydrogen from various fuels. Ballard Power Systems has achieved a more than 30-fold reduction in the platinum requirements for its fuel cell, and efficiencies near 80 percent [53].

While use of fuel cells can lower local air pollutants, their production does create environmental impacts. Martin Pehnt, of the German Aerospace Agency, has examined the resource and environmental impacts of PEM fuel cells by looking at the full production process. In terms of cumulative environmental impact, the platinum group metals (PGMs), which act as catalysts, account for the majority of greenhouse gas, sulfur, and nitrogen emissions. The chief impact is the emission of sulfur from the production of these metals. Pehnt points to several options for improving the ecological impact of fuel cells. PGM requirements can be reduced further and the metals recycled; the electricity source can be shifted to renewable energy; and components of the fuel cell stack can eventually be eliminated or recycled [54].

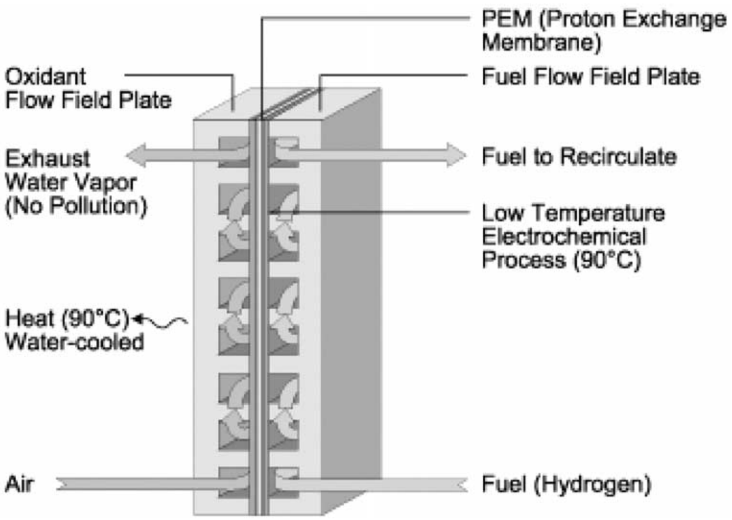

Fig. 8. A proton exchange membrane fuel cell. Source: see [53].

More than 100 organizations are researching or developing PEM fuel cells, which can be combined in stacks to serve a variety of applications, including the replacement of batteries in portable uses such as cell phones and laptop computers. Shell plans to distribute small DCH Technology fuel cells for use as battery replacements and range extenders in Iceland. Ballard is joining with Coleman to develop the Powermate, a portable fuel cell unit that can be used for camping and power tools. Motorola is developing small fuel cells for military uses in backpacks [55].

Stationary applications for fuel cells are also being intensively pursued. H Power is offering units from 35 to 500 W for back-up power, telecommunications, road signs, and residential uses. Ballard is working on stationary systems from 1 to 250 kW, in tandem with GPU, Alstom, and Ebara. Plug Power is partnering with GE Power Systems to distribute its 7-kW system globally, beginning in 2002. The two are also cooperating with Vaillant, the German heating system manufacturer, to deploy a fuel cell heating system for residential homes, with sales also starting in 2002. All of these units derive the hydrogen from natural gas, propane, or methanol through reforming units [56].

Transportation options are evolving quickly as well, with all major automakers investing billions of dollars in fuel cell development and planning the rollout of their first commercial vehicles between 2003 and 2005. Pilot tests of fuel cell buses running on liquid or compressed hydrogen have already been or are being conducted in Vancouver, Toronto, Chicago, Palm Springs (California), Berlin, Hamburg, and Munich, Copenhagen, Oslo, Lisbon, and Turin (Italy). In the largest fuel cell bus effort to date, Ballard is supplying 200-kW modules for 30 buses through XCELLSIS, a joint venture with Ford Motor Company and DaimlerChrysler. The buses will be delivered to nine European cities — Amsterdam, Barcelona, Hamburg, London, Luxembourg, Porto (Portugal), Reykjavík, Stockholm, and Stuttgart (Germany) — for transit purposes, starting in 2002, under a program partially funded by the European Union. BP is planning to deploy hydrogen-fueled buses in Perth, Australia, later this year. Buses are a starting point for the Iceland hydrogen economy effort, which will then move to passenger cars and fishing vessels, with the goal of completing the transition between 2030 and 2040 [57].

Hydrogen-powered buses are considered a logical first step for introducing fuel cells because they can handle larger and heavier ones, can store large amounts of compressed hydrogen gas on tanks on the roof, and can be refueled at central locations. The first public hydrogen fueling station was opened at the Munich airport in Germany. Other hydrogen fueling stations have been built in Las Vegas (Nevada); Dearborn (Michigan); and Hamburg, with stations in the works in Milan (Italy); Reykjavík, and Osaka and Takamatsu (Japan). The headquarters of the California Fuel Cell Partnership, which opened in November 2000 in the state capital of Sacramento, features a hydrogen refueling station — although the partnership is also exploring methanol and gasoline fueling stations, reflecting an emerging debate about the future of fuel cell cars [57,58].

The widespread introduction of hydrogen into car fleets faces three more difficult technical challenges. The first — integrating small, inexpensive, and efficient fuel cells into the vehicles — can be addressed through improvements in power density and lower platinum requirements. The second — designing tanks that store hydrogen onboard — can be tackled through vehicle efficiency gains, tank and vehicle redesign, and continued advances in storage technologies such as lightweight composite tanks, carbon nanotubes, and metal hydrides. The third challenge, developing an infrastructure for producing and delivering hydrogen, is the most significant and environmentally consequential. How this challenge is met will depend in large part on how automotive and energy companies choose to obtain the hydrogen [59].

5. The fuel choice question

The early days of the horseless carriage were a technological whirlwind, with transportation businesses racing to determine the standard engine for the vehicle of the future. In 1900, there were three candidates — electric battery-powered engines, with a 40 percent market share; steam-powered engines, comprising another 40 percent; and internal combustion engines running on gasoline, accounting for the remaining 20 percent. It might seem hard to believe today, but it took two decades for the ICE to establish itself as the dominant technology [60].

The next few decades seem to be shaping up similarly for the "ICE-free" vehicle. As fuel cells approach commercialization, transport and energy companies are experimenting with — and debating — the type of vehicle to mass produce and the type of fuel to provide through pipelines and at refueling stations or with a different infrastructure. These options range from the use of onboard gasoline and methanol reformers to the direct onboard storage and use of compressed gaseous and liquid hydrogen. Though there may not be one single "winner", as there was a century ago, some approaches may become dominant and lock out the others for years, with important repercussions. A particularly pressing question is whether the environmental implications of fuel choice — where the hydrogen will come from — are being adequately considered in strategies for deploying fuel cell vehicles [17].

The range of opinions on the "fuel choice question" among global fuel cell experts is illustrated by a fall 2000 survey prepared for the US Defense Advanced Research Projects Agency (DARPA) by the Northeast Advanced Vehicle Consortium (NAVC). More than 40 authorities from the government, industry, and research sectors were interviewed on major hydrogen fuel-related issues, and their responses reflect a mix of broad consensus and sharp disagreement. Most experts believed that hydrogen stored on board the vehicle and used directly was the simplest and most elegant solution, and would be the long-term choice for both passenger and transit fuel cell vehicles. The majority also felt that government R&D should focus on hydrogen storage technology as the best means of accelerating the commercialization of fuel cells [61].

Experts did not agree, however, on whether the direct use of hydrogen on board vehicles would happen in the near term. One interesting finding from the NAVC survey was the opinion of many experts that there would not be one "global fuel choice". Instead, the hydrogen could come from many feedstocks, with different geographical regions selecting the hydrogen feedstock that is most appropriate. Iceland, for example, might choose electrolysis from geothermal energy, while Texas picks compressed hydrogen from natural gas. The overall emissions would accordingly depend on the feedstock and the process of reformation [61].

Nor did the experts surveyed by the NAVC reflect consensus on the best fuel for on board reformation, if that should happen. Methanol was an especially divisive issue, with more opposed to the fuel than favoring it, and with the health and safety concerns raised by methanol often cited. Gasoline reforming also split opinion, with only a few automakers — but all energy companies — supporting it. Hydrogen providers opposed onboard reforming. Most experts did agree, however, that the fuel cell transportation market will develop first in the bus fleets subsidized by the government; that significant use in the passenger vehicle market is a decade away; and that codes and standards related to hydrogen storage and transport need to be worked out in the near term before fuel cell vehicles can achieve any significant market share [61].

As the NAVC survey revealed, each fuel has its advantages and drawbacks, which are in turn emphasized and de-emphasized by their advocates and detractors. Methanol is the easiest of the liquids to reform on board, and its reformer technology is several years ahead of that of gasoline reformers in terms of development. But it raises health and safety — and industry liability — concerns, as it is a classified toxin and has an invisible flame when burned. Methanol also mixes with water and, if spilled, could spread through groundwater more easily than gasoline. Furthermore, methanol would require changes in the gasoline distribution and storage apparatus — changes that might not justify the investment if methanol is an interim step to hydrogen [61].

Gasoline, meanwhile, is more difficult to reform than methanol because of the high temperatures needed for the reformation process. This would mean several years' delay in the introduction of fuel cell vehicles if gasoline is chosen as the liquid fuel. On the other hand, the fuel already has an existing infrastructure — and is therefore widely available — and is familiar to consumers. Yet selection of gasoline as the onboard choice might weaken the momentum to move toward a hydrogen-based system if commercially viable gasoline reformation becomes dominant [61].

One way to clarify these issues is to compare the ecological benefits of switching to hydrogen fuel cell vehicles by conducting "well-to-wheels" assessments. These evaluations examine the environmental impacts associated with the use of a fuel through each stage, from production to delivery to use, and can be measured in emissions as well as resource consumption and energy use. To date, several studies have focused on the overall greenhouse gas emissions of various hydrogen production systems. Each of these studies carries its own set of approaches, assumptions, and conclusions, which have stimulated broad debate and disagreement. But collectively, they provide a useful window on the complexity and ecological importance of the fuel choice issue [62].

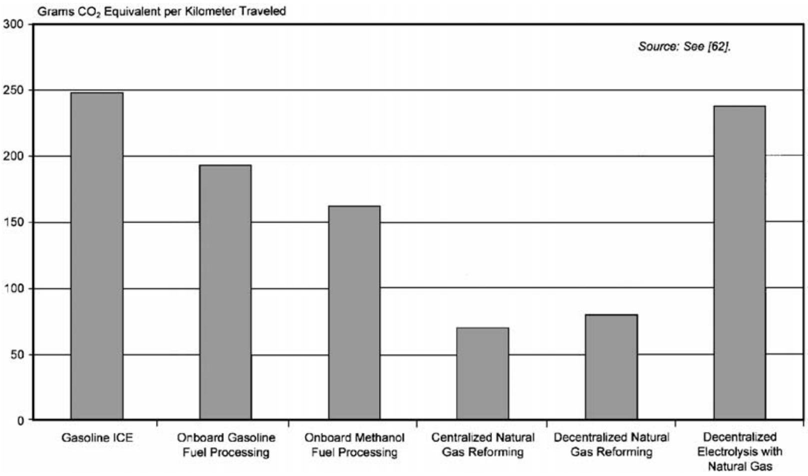

Fig. 9. Well-to-wheels greenhouse gas emissions from gasoline ICE and hydrogen fuel cell vehicles.

One of these studies, conducted in mid-2000 by the Pembina Institute, a Canadian research group, explored the well-to-wheels emissions of carbon dioxide, methane, and nitrous oxide for five different hydrogen production systems, supplying a car traveling 1000 km. These were compared with the baseline emissions of a gasoline ICE vehicle (see Fig. 9). The study found that a decentralized natural gas reforming system posed the fewest technical challenges and was the most cost-effective hydrogen production system, reducing life cycle greenhouse gas emissions by as much as 70 percent compared with conventional engines. Decentralized electrolysis achieved little reduction when based on fossil energy — in this case the system examined was a combined cycle gas turbine — but could attain significant emissions cuts if based on renewable sources. By comparison, the onboard fuel processing of gasoline and methanol resulted in 20–30 percent fewer greenhouse gas emissions [62, Fig. 9].

With regard to infrastructure needs, the Pembina study found decentralized natural gas reforming and electrolysis systems to be the most feasible options. This is because they can be expanded incrementally, as the fuel cell vehicle fleet expands, and do not require a radical overhaul. These systems can also use existing natural gas and electrical grids, in contrast to the methanol or centralized hydrogen production systems. Pembina is now undertaking, in collaboration with Suncor Energy, BC Hydro, and Ballard, a broader life cycle analysis and comparison, including other aspects of environmental performance — air emissions, water effluents, solid waste — as well as fuel and infrastructure costs. Its initial report has attracted some media attention, as it implied that the preferred choices for many companies — gasoline and methanol — offered the least improvement in terms of emissions reduction, while natural gas — relatively ignored by industry — offered the greatest climate benefits. But, according to the Ottawa Citizen, the Pembina pollution rankings "have been all but ignored in the race to retain market share in the pending hydrogen economy" [62,63].

Another well-to-wheels study related to hydrogen was published by the Massachusetts Institute of Technology (MIT) Energy Laboratory in October 2000. The MIT researchers examined the life cycle greenhouse gas emissions of new automobile technologies that could be developed and commercialized by 2020. The study compared ICE cars, hybrid ICE and hybrid fuel cell cars — combining an engine and electric battery — and battery electric cars, assuming that in 2020 hydrogen would be manufactured by reforming natural gas in decentralized refueling stations. The hydrogen would then be dispensed into tanks of fuel cell cars. Other options, currently more expensive, involve electrolyzing of water at the service station, reforming natural gas in centralized facilities, and either piping compressed hydrogen or trucking liquid hydrogen to service stations. In any of these cases, significant new investments would be necessary [64].

Hybrid ICE and fuel cell hybrid vehicles were found to be the most efficient and least polluting, offering greenhouse gas emissions cuts of up to 50 percent below the baseline technology. But they also cost up to 20 percent more to purchase and use. If automobile systems are expected to achieve even lower emissions, the study suggests, the only feasible options will be hydrogen produced by renewable energy, or from fossil fuels with the carbon sequestered [64].

A key finding of the MIT researchers was that fuel cell vehicles with a liquid fuel reformer on board "do not appear to offer any energy use benefits over the advanced body gasoline vehicle, and are inferior in performance to the similar fuel ICE hybrid options considered". However, the report also noted "comparatively large" emissions and inefficiencies associated with the production and distribution of hydrogen. If hydrogen is stored on board, both energy use and greenhouse gas emissions are reduced by about 30 percent, with local emissions almost completely eliminated. This will, however, require reductions in the weight and volume of current onboard hydrogen storage technologies, perhaps through carbon nanotubes. The study was presented to the media as demonstrating that the environmental benefits of fuel cell vehicles might be overstated: author Malcolm Weiss told a Technology Review reporter that "fuel cells offer no important advantages over other technologies… . You can more quickly and easily introduce and produce improvements in traditional and new technologies" [64,65].

Another recent well-to-wheels analysis, released in March 2001, was led by GM in conjunction with the US Argonne National Laboratory, BP, ExxonMobil, and Royal Dutch/Shell. Evaluating 27 combinations of fuel and propulsion systems to determine which was the most energy-efficient and produced the fewest emissions, this study found that the best performers in energy use were gasoline reformer-based hybrid fuel cell vehicles and hybrid fuel cell vehicles using direct hydrogen, derived off board from natural gas. In terms of greenhouse gases, hybrid fuel cell vehicles using ethanol emitted the least, followed by the direct hydrogen fuel cell vehicles. The gasoline-based hybrids placed fourth in greenhouse gas emissions. In a press release accompanying the study, GM announced that its findings supported gasoline-based fuel cells as the "cleanest and most efficient alternative" to traditional auto engines "until storage and distribution systems are developed that support fuel cells served directly by hydrogen". GM is a leading advocate of gasoline reformers, having hired at least 200 engineers and devoted several billion dollars to a project with ExxonMobil aimed at becoming the first automaker to have 1 million fuel cell vehicles on the road. The goal is to begin mass production by 2010. The company acknowledges that there will eventually be a switch to a hydrogen-based infrastructure, and says its goal is to move the reformer off the vehicle and have hydrogen available at the gas pump. But it believes that placing the reformer on the vehicle is the fastest way to get the technology to market [66].

As one might expect, trade groups have also come out with literature promoting their particular fuel. The American Petroleum Institute has released a pamphlet suggesting that gasoline and methanol are the two major choices. The paper supports gasoline, contending that methanol and hydrogen infrastructures "must provide significant benefits over alternatives that can use existing infrastructure". The American Methanol Institute takes an opposite tack in its report, arguing that the gasoline fuel cell vehicle is a decade behind efforts to commercialize the methanol fuel cell vehicle. The report quotes Jason Mark, an analyst with the nongovernmental Union of Concerned Scientists: "There is no reason to cram yesterday's fuel into tomorrow's technology…. Fuel cells that run on clean fuels put us in the fast lane to ending smoggy skies and oil dependence. Why take a detour through gasoline?" [67].

Environmental groups are beginning to weigh in on this issue. The World Wide Fund for Nature (WWF)-Europe and Icelandic Nature Conservation Association have lent support to the Iceland hydrogen initiative, whose six-phase plan was unveiled in March 2001. The plan will begin with three hydrogen buses in Reykjavík, then move to replace all buses with fuel cells, repeating the process for the car and fishing fleets. It will also study the production of methanol from a ferrosilicon plant, and the consortium may decide to use methanol-based fuel cell vehicles. The non-governmental groups estimate that the goal can be met entirely from Iceland's renewable energy, primarily existing hydro and geothermal power and new offshore wind projects. They also hope that Iceland's example will spur the European Union to better support hydrogen storage and infrastructure development. Giulio Volpi, of WWF-Europe, argues that "zero or near-zero emissions of greenhouse gases can only be achieved by hydrogen produced from renewable energy, such as hydro, wind, or biomass. In contrast, gasoline-based fuel cells will bring little or no benefit to the climate" [68].

A number of energy experts worry that the emphasis on onboard fuel processing will have negative ecological consequences. In a 1999 paper from the Hydrogen Technical Advisory Panel (HTAP), a group of scientists charged with providing hydrogen policy advice to the US government, argues that both industry and government are "providing substantially greater support for onboard fuel processing — despite the significantly greater long-term societal benefits of direct hydrogen". Relative to gasoline reformers, direct hydrogen would reduce both greenhouse gas emissions and reliance on imports. Yet if the onboard processor option were to attain market dominance, it could lock out direct hydrogen vehicles for decades to come — missing the important benefits that such vehicles would provide. Inferior technologies have, in fact, locked out rivals in the past — VHS over Beta in the videocassette market, and Windows over Macintosh in the personal computer market. "But", the paper argues, "we have a long way to go to convince car makers and energy suppliers that direct hydrogen represents an early, viable pathway to eventual widespread usage of fuel cell vehicles" [17].

Despite their apparent leaning toward fuel processors, the auto and energy industries face what Richard Stobart of Arthur D. Little refers to as the "hydrogen paradox: 'Can the development of fuel processing technologies develop with confidence when it is quite possible that they will be replaced in a short time by a straight hydrogen fuel solution?'" This debate, he notes, echoes somewhat the hydrogen economy debates of the 1970s, and will continue for some time. It also explains why, as one executive has put it, "everyone is placing bets on several horses" [17,69].

Energy companies are clearly weighing their options. BP is exploring both methanol and gasoline, and has followed

Shell's lead in creating a hydrogen division. Shell CEO Mark Moody-Stuart has stated that "in Shell we believe the way forward is through onboard conversion of gasoline to hydrogen". In June 2001, Shell Hydrogen and International Fuel Cells formed a joint venture to produce fuel processors. Paul Berlowitz of ExxonMobil, which favors gasoline, acknowledges that "the question of fuel choice for fuel cell vehicles remains an open one". But he contends that "the major practical barrier to widespread introduction of fuel cell vehicles is the need to provide hydrogen to the fuel cell. Development of onboard storage may be practical in the future, but will require a large R&D effort. At this time, a practical solution for hydrogen storage is not available". Texaco has invested in Energy Conversion Devices, a maker of metal hydride hydrogen storage technologies. Texaco's Gene Nemanich insists that his firm is "fuel neutral....seeking a new path, not preserving the old guard" [70].

Automakers are also of necessity keeping their options open. Most leading automakers have tested at least one direct hydrogen vehicle. Ferdinand Panik of DaimlerChrysler, which has committed $1 billion over 10 years to fuel cells, believes that "hydrogen and methanol appear to hold the greatest promise". Frank Balog of Ford sees the fuel cell as a "game-changing technology...if we're not in the fuel cell business, we may not be in the auto business"; his company is testing both direct hydrogen and methanol vehicles. Honda has unveiled both hydrogen- and methanol-based cars. In January 2001, Toyota joined the GM– ExxonMobil alliance to develop gasoline-based fuel cell cars. In June 2001, Nissan and Renault announced they would make gasoline-based fuel cell cars their priority [71].

Even GM, with its advocacy of gasoline-based fuel cell vehicles, is hedging its bets. In June 2001, the company made major investments in two hydrogen technology companies: Quantum Technologies and General Hydrogen. Quantum has developed a high-pressure storage tank, and General Hydrogen specializes in delivery and refueling systems. The latter of these is chaired by Geoffrey Ballard — founder of Ballard Power Systems and father of the fuel cell industry — who, when asked for his opinion about where the hydrogen should come from, replied that he was "agnostic". But one of the most revealing comments came from GM executive Larry Burns, who asserted that, in the "race to affordability" for fuel cell vehicles, significant investment from federal and state governments will be a key factor in developing the necessary hydrogen infrastructure [72].

6. Greening the infrastructure

The challenge facing the hydrogen economy provides a textbook example of the "chicken-and-egg" dilemma of introducing an alternative fuel. Automakers are loathe to mass produce direct hydrogen fuel cell vehicles if they cannot be guaranteed that there will be an adequate number of hydrogen refueling stations in place to supply their customers. Energy companies, on the other hand, are reluctant to build hydrogen refueling stations if they do not anticipate significant demand for the fuel. This has led experts to view the building of a hydrogen infrastructure as an insuperable obstacle, and to peg the costs of this endeavor at the hundreds of billions of dollars — $100 billion for the United States alone, according to the Department of Energy — many more times than a liquid-based infrastructure. A number of recent studies, however, suggest the reverse: that the direct use of hydrogen may in fact be the quickest and least costly route [73].

Sandy Thomas, an analyst with Directed Technologies, is among those exploring the real cost of moving straight to a hydrogen infrastructure that can support fuel cell cars and buses, and ultimately power plants. Thomas and colleagues argue in a recent article in the International Journal of Hydrogen Energy that "the total fuel infrastructure cost to society including onboard fuel processors may be less for hydrogen than for either gasoline or methanol". In addition, the authors show that hydrogen fuel cell vehicles present distinct advantages over those run by gasoline and methanol in terms of local air pollution and greenhouse gases. Nevertheless, Thomas believes that either of the latter fuels could well be chosen by industry, impeding the direct approach [74].

In earlier studies conducted for Ford Motor Company — in league with three industrial hydrogen producers, Air Products, BOC Gases, and Praxair, and an electrolyzer manufacturer, the Electrolyser Corporation — Thomas has shown that hydrogen could be supplied to fuel cell vehicle owners at a cost per mile that is "near, or even below", that of gasoline in a conventional vehicle in the United States. At first, when there are few new vehicles, small-scale, factory-built steam methane reformers or electrolyzers could be used to serve the small fleets. This way, the existing natural gas pipeline system or electrical grid would be utilized, with hydrogen produced when and where it is needed. These smaller appliances could allow the hydrogen industry to grow with the fuel cell vehicle fleet, avoiding the risk of committing to large investments before many cars are being sold. They could also provide the automobile industry with the confidence to manufacture direct hydrogen fuel cell vehicles, by ensuring that widely dispersed fueling sites will be available. Excess hydrogen from the chemical industry could also be tapped [75].

Researchers at the University of Michigan have also explored the path to a direct hydrogen infrastructure. Marc Jensen and Marc Ross likewise recommend the use of small-scale natural gas reformers at fueling stations, relying on existing natural gas pipelines to distribute the fuel. They estimate that building 10,000 such stations — 10–15 percent of the total number of US filling stations — would be enough to motivate vehicle manufacturers to pursue mass production of direct hydrogen fuel cell vehicles [59].

Such bridging strategies require capital investments — $3–15 billion in this case, the authors estimate. But this sum, note Jensen and Ross, "can be weighed against the social and environmental benefits that will be gained as a fleet of hydrogen-fueled vehicles grows". The cost of air pollution in the Los Angeles basin, for example, is estimated at $8 billion per year. Hundreds of billions of dollars may in fact need to be invested over decades in a network of underground pipelines engineered specifically for hydrogen. But it is misleading to suggest that this entire sum must be spent up front. Jensen and Ross argue that direct hydrogen makes the most sense from a longer-term financial and environmental perspective, and that the greater cost may lie in potential stranded assets, especially if the gasoline infrastructure is subsidized beyond the point at which the fuel becomes more expensive than hydrogen. They contend that by the time reformers became widespread in fleet, direct hydrogen may have become the most economical choice [59].

Another direct route to hydrogen has been proposed by Amory Lovins and Brett Williams of the Rocky Mountain Institute (RMI). Lovins and Williams argue that the two presumed roadblocks — that a large infrastructure for producing and distributing hydrogen would cost hundreds of billions of dollars in the United States, and that a technological breakthrough is needed to store compressed hydrogen directly onboard the vehicle — simply do not reflect current technological and market trends. They contend that structural changes in the vehicles can improve efficiency enough to permit onboard hydrogen storage. And they assert that fuel cells in vehicles can be integrated with buildings in a manner that will improve their economics and postpone any need to create a full-blown hydrogen infrastructure [76].

Lovins and Williams propose a three-step process for jump-starting the US hydrogen economy. In the first step, fuel cells are deployed in buildings, which account for two-thirds of energy use in the United States and similarly large portions in other nations. These fuel cells reuse their waste heat for higher efficiency, and operate on hydrogen from a natural gas reformer or off-peak electrolyzer. Wide deployment in buildings increases production and cuts manufacturing costs to levels that make fuel cells competitive in high-efficiency vehicles [76].

The second step would be to integrate super-efficient "hypercars" — lightweight prototype vehicles made of carbon fiber, built and patented by RMI — with buildings, where off-peak electrolyzers can produce and deliver hydrogen. The vehicles can be used like appliances as "plug-in" power plants, with a 20-kW capacity, with the revenues they generate used to pay for the costs of leasing the building. This would make direct gaseous hydrogen use practical without a full supply and distribution infrastructure, and would work better and cost less than onboard liquid fuel reforming to produce hydrogen. The more than three terawatts of US generating capacity that result would be enough to displace most central thermal power stations [76].

The third step in the RMI strategy shifts hydrogen production upstream, as fuel cell deployment in buildings and vehicles brings down the cost of dispersed stationary reformers and electrolyzer appliances, which are increasingly installed. The growing hydrogen market would prompt other supply options, such as renewable electricity and reforming natural gas at the wellhead. But the authors warn that the failure of carmakers to realize the very low costs of a direct hydrogen system would lock in extra capital costs of more than $1 trillion for the next car fleet and its liquid fueling infrastructure. It would also lock out a more diverse, environmentally benign supply of fuels [76].

The feasibility of these analyses is supported by the assertion of a 1999 National Renewable Energy Laboratory (NREL) infrastructure workshop report that "there are no technical showstoppers to implementing a direct hydrogen infrastructure". This was a consensus collectively reached by major auto, energy, and hydrogen companies, agencies, national laboratories, and universities. The participants pointed to the need for engineering improvements, codes and standards, and the resolution of other institutional issues. But company representatives felt that they were technically capable of proceeding with the development of the infrastructure and technologies for hydrogen markets. The issue is the timing and coordination of capital investments, and the need for government and industry to collaborate in developing a roadmap [77].

The financing issue is one that Shell Hydrogen CEO Don Huberts has been investigating. Huberts, who argues that "there is a path to the pure hydrogen infrastructure", anticipates no technological "lock-in", but rather the onboard fuel processing and direct hydrogen vehicles developing in tandem, with the former serving primarily to introduce people to fuel cell cars. The smaller fleet market of hydrogen vehicles would then evolve into a mass market, as a full infrastructure developed in incremental steps out of the retail stations serving the initial fleet. Meanwhile, the cost of fuel cells and other components would decrease with mass production, fiscal incentives for cleaner vehicles, and improvements in hydrogen storage [78].

Huberts sees single refueling sites, for buses and delivery vehicles, evolving into multiple sites across the region that would serve commuter and family cars as well. These greater numbers of retail stations would provide economies of scale, lowering the cost. In addition, an increasing proportion of the hydrogen would be based on renewable energy, providing carbon-free mobility. Huberts estimates the cost of providing hydrogen to 400,000 fuel cell vehicles in California by 2020 at $1.2 billion. The total cost of an initial nationwide hydrogen infrastructure would be $19 billion in the United States, $1.5 billion in the United Kingdom, and $6 billion in Japan [78].

Huberts' research, suggesting that the hydrogen infrastructure's cost may be overestimated, takes on added importance when one considers how the liquid-based infrastructure costs may be underestimated. Joan Odgen, of Princeton University's Center for Energy and Environmental Studies, writes that "the conventional wisdom that hydrogen infrastructure is much more capital-intensive than methanol and gasoline is true only for small market penetration of hydrogen or methanol vehicles". Once a large number of alternatively fueled vehicles are on the road, she points out, the capital cost is great for developing any new fuel. Production plant costs are higher for both methanol and gasoline, furthermore, and hydrogen can be used about 50 percent more efficiently on board a vehicle. And the costs of maintaining or expanding a gasoline refueling infrastructure cannot be neglected, running several hundred dollars per car. Including the total infrastructure costs, she estimates that methanol and gasoline fuel cell vehicles will actually cost $500 and $1000 more per car, respectively, than hydrogen vehicles [79].

When environmental damage is factored in, direct hydrogen cars look even better. In a forthcoming study, Ogden and colleagues Robert Williams and Eric Larson explore options for achieving a transportation system that had zero emissions of both air pollutants and greenhouse gases, and that diversified the supply system away from petroleum. The study compares automotive engine and fuel options that evolved toward these goals, estimating their performance, fuel cycle emissions, and life cycle costs. The study uses a broader yardstick than previous studies, "societal life cycle costs", which includes direct consumer costs as well as environmental damage costs (see Fig. 10). Unlike the Pembina, MIT, and GM studies, the Princeton study includes air pollution damage in the calculation [80].

The Princeton team found that the hydrogen fuel cell vehicle stood out as causing the least environmental damage, and cost one-eighth as much as the gasoline hybrid ICE vehicle. In addition, fuel cell vehicles using hydrogen directly were found to offer much lower life cycle costs than those using onboard fuel processors based on gasoline or methanol — with the difference ranging from roughly $550 to $2500. At the same time, hydrogen fuel cell vehicles were not as competitive with gasoline hybrid ICE cars if environmental benefits were not taken into account. The cost of delivering the hydrogen to the cars was not projected to be much higher than that for gasoline — $2–$3.50 per gallon of gasoline equivalent — and would be more than offset by the efficiency of the hydrogen fuel cell vehicles, expected to be three times that of gasoline ICE cars [80].

A key uncertainty in these findings is whether the 40-fold reduction in the cost of a fuel cell drivetrain — from $200,000 per car to $5000 — that is needed to compete with a gasoline hybrid car will be achieved by mass production. The Princeton researchers recommend the use of centrally refueled fleet vehicles, such as government or corporate car or truck fleets and urban transit bus fleets, for launching the fuel cell vehicle technology. This would put off the hydrogen infrastructure problem until the fuel cell costs have been "bought down" to competitive levels, at which point there would be a strong impetus to further develop the hydrogen infrastructure. This approach could also use existing compressed gaseous hydrogen technologies, avoiding the need for a storage breakthrough, and provide a useful base of experience for demonstrating the vehicle and increasing consumer acceptance [80].

The Princeton study shows that markets for centrally refueled fleet vehicles are big enough for this buydown of fuel cell costs. It also notes that the cost of this strategy will be far less than that of either the gasoline or methanol strategies for launching fuel cell vehicles in the market. "These findings call into question the wisdom of strategies currently being pursued by most automakers, which are aimed at commercializing FCCs (fuel cell cars) using either methanol or gasoline as the initial fuel". By redirecting commercialization efforts away from these currently popular strategies, and toward hydrogen fueling strategies for centrally refueled fleets, the authors conclude, fuel cell costs can be brought down to competitive levels faster — and with fewer financial resources [80].

Ogden and her colleagues believe their path is realistic: "There are plausible futures for transportation based on advanced technologies, notably hydrogen fuel cell vehicle-based futures, that could provide transportation services at direct economic costs that are not much higher than at present but that offer the potential for near-zero emissions of both air pollutants and greenhouse gases, while simultaneously making it possible to diversify transportation energy away from the present near-exclusive dependence on oil". But they emphasize that environmental concerns will be a critical determinant of whether such "radical" innovation takes place in automotive technology, and that "the most likely scenario in which the hydrogen fuel cell vehicle emerges as a major option is in response to strong policy measures", such as zero-emission mandates and tax incentives that would steer car innovation toward the cleanest options. They cite as an example the California mandate, which requires that 10 percent of vehicles sold in the state in 2003 be "zero-emission". These provisions have been modified to allow direct hydrogen and other vehicles to qualify, and have spurred both worldwide fuel cell development and the California partnership. Which hydrogen future is chosen will result, in no small measure, from public policy and its influence in moving industry toward the cleaner solutions [80,81].

7. Building the hydrogen economy

> I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth [82].
>
> — US President John F. Kennedy, May 1961.

> If we really decided that we wanted a clean hydrogen economy, we could have it by 2010 [83].
>
> — US National Renewable Energy Laboratory researcher, April 2001.

To watchers of the hydrogen world, the HYFORUM 2000 conference in Munich, Germany, was a watershed,

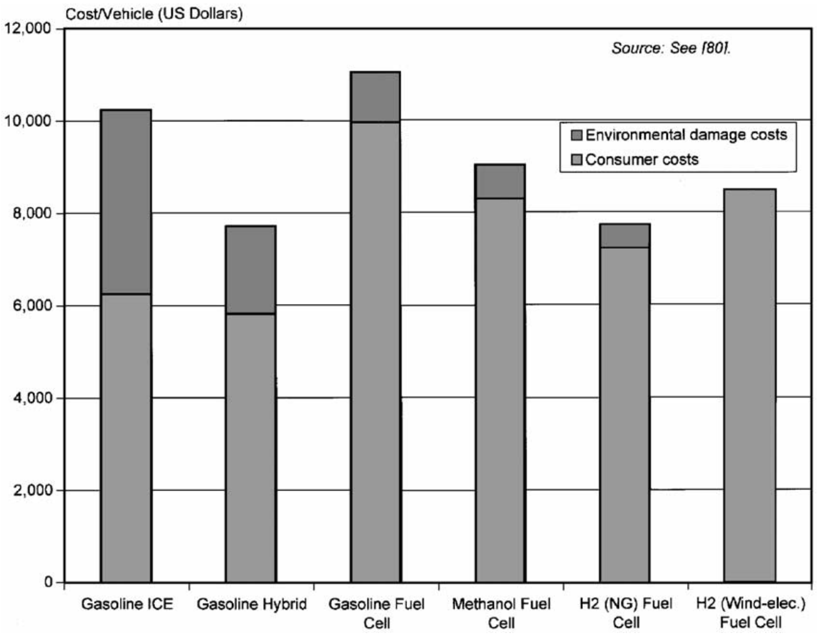

Fig. 10. Total life cycle costs, selected fuel/vehicle combinations.

attracting heavyweights from the political and business communities. German economic minister Werner Mueller opened the conference, arguing that the industrial sector needed a farsighted, overarching vision of the future. “Hydrogen energy technology is such a vision.... Regeneratively produced hydrogen is synonymous with an energy supply that is secure in the long term and is free of harmful emissions” [84].

Another first of the hydrogen conference was an emphasis on banking and finance. Representatives of the European Commission (EC), leading European commercial banks, the World Bank, and venture capital funds convened a roundtable to discuss the financing of the transition to a hydrogen economy. Several financiers were bullish about the hydrogen prospect. Robert Shaw of Aretê Corporation dismissed the $100 billion estimate of US infrastructure needs, arguing that all 100,000 US stations could be equipped with hydrogen dispensers for $20 billion — a figure he compared with the $30 billion spent on Internet companies in 1999. Tom Oates, a manager from Merrill Lynch, unveiled his firm’s new $300 million alternative energy fund, of which 30–40 percent would be invested in hydrogen-related technologies [84].

Ministers and bankers pointed repeatedly to the issue of distributing and storing hydrogen, especially the chicken-and-egg dilemma of refueling. The EC’s Guenther Hanreich, referring to changes in the European infrastructure, remarked that “intervention by the European Commission has proven able to break such circles in many cases in the past....[The dilemma] is too big to be handled by one company or one country. This key question should be discussed at least at the European level, and probably in cooperation with other industrialized countries such as the United States and Japan”. Private bankers from Merrill Lynch and Dresden Bank agreed, noting that, because of their need to provide a short-term rate of return, they could not finance a rapid transition on their own. Norbert Walker, chief economist of Deutsche Bank, called for guidance from regulatory agencies through emissions certificates or some other form of policy, suggesting, “Perhaps pressure should be applied to help along systems with the most obvious advantages” [84].

The case for government intervention in moving toward a hydrogen economy is nothing new. It dates back at least a quarter century, to a 1976 study by the Stanford Research Institute entitled *The Hydrogen Economy, A Preliminary Technology Assessment*. “Because the transition to hydrogen energy is genuinely only a long-term option and would take more time to implement than the private sector is normally concerned about”, its authors concluded, “the role of hydrogen in the future US energy economy is rightfully a matter of public policy” [85].

Judging from where the hydrogen economy has begun to emerge, there are at least 10 generic elements of a hydrogen policy, or types of measures that could help the transition along (see Table 5). A starting point is to correct the incentives for continued hydrocarbon production that, left alone, will continue to frustrate efforts to introduce hydrogen fuels.

Table 5
Ten elements of a hydrogen policy[a]

- Research and development
- Demonstrations
- Feasibility studies
- H_2 economy target dates
- Public-private partnerships
- Full-cost energy pricing
- Environmental regulations
- Tax incentives
- Codes and standards
- Public education

[a] Source: see [86].

These include the roughly $300 billion in annual supports for fossil fuel use, measured in direct supports and in environmental externalities such as air pollution and climate change. The negative effects of these market distortions can be lessened by phasing out direct supports, and by introducing fuel taxes that are offset by other types of taxes to remain revenue neutral. Otherwise, artificially low fossil fuel prices will continue to slow the hydrogen transition. At the same time, disparities in gasoline prices and taxes between Europe and the United States may help the former gain an edge in shifting to hydrogen [86].

Another integral part of the renewable-hydrogen economy blueprint is the feasibility assessment. As in the case of Iceland and Hawaii, such assessments enable countries to recognize their potential for becoming leading hydrogen producers and exporters. According to its own hydrogen feasibility study, Norway, with its large natural gas resources and production capabilities and expertise in producing hydrogen from electrolysis, “could become the leading nation in hydrogen production in a short period of time”. The report added that hydrogen production based on various renewable processes — water electrolysis, photolysis, biolysis, and biomass gasification — will be important future options. It recommended further research into these areas as well as into storage, transport, and fuel cells [87].

Indeed, research and development are urgently needed to promote innovations that have potential long-term benefit but unproven commercial potential — and that the private sector therefore cannot be expected to finance. A good example of this catalytic role of seed funding is DARPA, the US defense agency that is charged with exploring new and potentially high-impact technologies, and that laid the groundwork for the Internet infrastructure. As noted earlier, DARPA is involved in a public–private consortium to promote advanced fuel cell vehicles; the agency also funds a variety of lab research efforts to improve the efficiency of hydrogen-related technologies, which could have important military applications in vehicles and backpacks. In *Powering the Future*: *The Ballard Fuel Cell and the Race to Change the World*, Tom Koppel points out that Canada’s defense agency provided timely support to Geoffrey Ballard in the early days of what has become today’s well-financed Ballard Power Systems. More recently, Quantum Technologies has benefited from DOE R&D support to achieve the improvements in its storage tanks that attracted major investments from GM. Looking ahead, storage technologies and renewable-energy-based electrolysis deserve top priority for increased research funding [88].

Policy support for hydrogen varies among industrial nations, reflecting different cultures and emphases. In the United States, hydrogen is not well integrated with national energy policy, partly because of reluctance to address petroleum import dependence, an uncertain stance toward climate change, and the bias toward more established energy sources. Overall, there are 440 non-defense hydrogen-related projects funded in federal departments, totaling roughly $140 million per year. This includes a basic hydrogen program, which received around $27 million for the 2001 fiscal year [89].

Hydrogen is beginning to receive more attention in the ongoing US energy policy debate. In April 2001, President George W. Bush proposed a 48 percent cut in the basic hydrogen program budget. But the national energy plan sent to Congress in June restored funding to previous levels, and proposed income tax credits for fuel cell vehicles and reauthorization of the Hydrogen Future Act. The Act, which is due to expire in 2001, will likely be expanded beyond R&D to include the deployment of fuel cells in federal buildings and vehicles and in other locations. The Administration also announced the awarding of $120 million in investments — cost-shared with industry and academia — in new research to accelerate hydrogen and fuel cell development. Still, the proposed basic hydrogen program budget is roughly one-fifth that for clean coal technologies, and one-tenth that for nuclear power. Hydrogen expert Dr. Helena Chum believes that current funding levels, particularly for storage innovations, are “not sufficient for fast tracking the emergence of a hydrogen economy” [90].

Several international experts have also criticized the US commitment to hydrogen as weak, relative to the nation’s scientific and technological prowess. These critiques come primarily from parts of Europe, where hydrogen is a more visible element of energy policy. When some consultants at the HYFORUM 2000 conference likened the US hydrogen program to the “man-on-the-moon” Apollo space program, several European experts responded with skepticism. Iceland’s Bragi Árnason, father of the Iceland initiative, said he expected the US to be spending much more. He noted that, on a per capita basis, Iceland invests more in hydrogen than the United States does [91].

Hydrogen has stronger political support in Germany, which is the world leader in terms of the number of demonstrations of hydrogen and fuel cell vehicles, fueling stations, and renewables-based hydrogen production systems, as well as in the hosting of hydrogen conferences. The German government recognizes that hydrogen is critical to its long-term energy strategy, and is expected to make the fuel a higher priority in coming months. However, hydrogen expert Dr. Rolf Ewald contends that federal and EC funding for hydrogen is "decreasing and weak", with the most support coming from German states such as Bavaria [92].

The European Commission is increasingly active in supporting hydrogen, mainly through research and demonstrations. It currently funds 60 fuel cell projects at \$25 million per year. It also co-finances the European Integrated Hydrogen Project, a 20-industry-member effort to harmonize regulations and new codes, in the EU and globally, for hydrogen-fueled vehicles and filling stations. But it has also been criticized for having loosely connected programs, and the EC recently launched a "Thematic Network" aimed at coordinating hydrogen and fuel cell activities across the continent [93].

Japan's national program is considered the most ambitious and comprehensive of the world's hydrogen initiatives to date. Japan expects to spend about \$4 billion on its WE-NET (World Energy Network) program by 2020. Currently funded at \$88 million over 5 years, the program is involved in improving the efficiency of fuel cells, enhancing the storage capacity of metal hydrides; installing filling stations that will test out natural gas reformers and electrolysis; and testing cars using metal hydrides and compressed gas cylinders in partnership with Japanese automakers. Its scientists view natural gas reforming and electrolysis as the near-term infrastructure path, and hydrogen from renewable energy as the medium- to long-term route. However, WE-NET official Kazukiyo Okuno acknowledges that the program has not set any goals for introducing hydrogen into the market [94].

Greater international collaboration in supporting hydrogen is also needed. Twelve industrial nations are cooperating on hydrogen efforts under the auspices of the International Energy Agency (IEA). Under the agency's Hydrogen Implementing Agreement, created in 1977 to increase hydrogen's acceptance and wide use, the IEA has funded numerous research and development efforts and demonstration projects. The program is geared toward a hydrogen future with sustainable energy, and thus focuses on solar production, metal hydrides, and the integration of renewable energy and hydrogen systems. It is also working to engage other interested countries, like China, Iceland, and Israel [95].

Public–private partnerships form another common thread among the existing hydrogen efforts. Iceland provides an important example of how government, by indicating a supportive environment, can attract the innovation and financial resources of major multinationals to get the hydrogen economy moving. The California partnership, with its broad, international participation from nearly all major industry players and government at all levels, may also provide a useful blueprint, as well as a test-drive, for determining what hydrogen issues require government assistance. British hydrogen expert David Hart believes that "California could lead the way" to fuel cells and hydrogen more generally. But he notes that this partnership might not have come about without the state's strict clean air regulation. Similarly, Iceland's impending greenhouse gas restrictions also played a role in spurring interest in hydrogen. Such collaborations may be a useful complement to, but not necessarily a substitute for, regulations and incentives [96].

One challenge facing governments in their effort to support the research, development, and deployment of hydrogen technologies is the uncertainty as to what lies ahead, 10–20 years down the road. How can policymakers better link long-term vision with short-term funding decisions? The US Hydrogen Technical Advisory Panel has tried to address this problem by creating a set of scenarios describing how events might unfold, with an eye to recommending how the government should strategically invest in energy [97].

The panel came up with four scenarios, reflecting different rates of technological development, emphases on market forces, and levels of social concern. In the most utopian future, "Brave Clean World", technologies and policies come together to achieve rapid hydrogen development. In "Hydrogen Genie", market-driven competition moves toward the new fuel, albeit less quickly. In "New World, Old Weapons", conventional fossil fuel technologies are improved significantly and become the main hydrogen carrier. And in "Hydrogen in a Bottle", the fuel is limited to niche markets. Based on the current state of affairs, the team agreed that hydrogen is trapped "in a Bottle" and could move on a trajectory either directly toward the "Genie" or indirectly through the "New World, Old Weapons" and "Brave Clean World" futures. Which path is taken will depend on hydrogen policy — the mix and ambitiousness of research and development, regulations, and incentives adopted. The team will use these scenarios to recommend an investment strategy for the government, which could lead to a greater emphasis on moving directly to hydrogen [97].

Also examining hydrogen futures are corporations, notably Shell, a pioneer in scenario planning and the first large energy company to create a core hydrogen business. Shell sees two types of major transition paths: one based on completely new, carbon-free energy sources, and the other rooted in existing, mostly fossil-fuel-based, infrastructure. The carbon-free path, based on a new renewables infrastructure, would rely on electrolysis, using — in some models — solar or wind power to produce hydrogen, potentially on a relatively large scale and in remote locations. The gas would then be piped to the points of consumption [98].

Shell sees the carbon-free path constrained, however, by the cost of building the renewable installations, generating the electricity, converting it into hydrogen, and creating the infrastructure of pipes, storage, and distribution. To justify such investments, renewable energy would have to become cost-competitive and hydrogen markets more developed. This process would have to be developed by fully costing the environmental impact of conventional energy sources. As Mark Moody-Stuart, Shell CEO, has said, "This is clearly the best possible system — completely emission free and environmentally benign. The question is how to get there" [98].

Shell's scenarios thus point to a clear government role in facilitating the hydrogen transition. Moody-Stuart warns against politically driven technology choices — such as the Concorde airplane and HDTV — that have wasted tens of billions of dollars and yet failed to create viable technologies. At the same time, there is a legitimate political interest in environmental improvement and limiting CO_2 emissions. Shell believes that "targets should be set and then industry should be allowed to get on with experimenting and developing different technologies". If companies have the freedom to experiment, and if governments create the conditions favorable to introduction of environmentally preferable products, and if the public is educated about the products, then customers will make the right choice. "That is the way to make rapid progress and to introduce hydrogen technologies — through a broad market focus, guided, but not controlled, by benign government regulation" [98].

When the hydrocarbon era was gestating in the early 1900s, few could have imagined the enormous economic, political, and ecological repercussions that this new energy source would have in coming decades. War, politics, commerce, lifestyles, and the natural environment were all shaped and irrevocably altered by the fuel, leading some historians to term the 20th century the century of oil. The history of the hydrocarbon era in the 20th century has been thoroughly documented in Daniel Yergin's classic book *The Prize*. As Yergin observes, the story of oil contains three large themes: the rise of capitalism and modern business; the link between energy and national strategies and global politics; and the development of a "hydrocarbon society" [99].

If hydrogen is, as some scientists call it, "tomorrow's oil", what does the dawning century of hydrogen hold in store for us? What will the advent of the hydrogen age mean for Yergin's themes? How will this new energy source affect business, politics, and society? It is too soon to tell. But like the hydrocarbon era now coming to a close, the hydrogen era could very well create its own powers and prizes [100].

Indeed, the evolution of this new system is already beginning to transform the energy industry, with oil companies repositioning themselves as energy firms — and raising intriguing questions of competitive strategy. Which energy companies will survive the transition by genuinely moving, as BP has branded itself, "beyond petroleum" and aggressively pursuing the hydrogen market? Which transport companies, replaying US–Europe–Japan rivalries, will make the right choices about fuel and infrastructure, establishing dominance in the fuel cell vehicle market? Which big electric power companies will repeat the mistakes of IBM, losing market share as their industry becomes more decentralized and entrepreneurial [101]?

The winners in the hydrogen market may or may not be those who have dominated the hydrocarbon business. John Browne's philosophical stance on the future of energy may provide an appropriate strategy for companies pursuing the hydrogen market. "I believe the challenge — the business challenge — is to transcend the sharp tradeoff...that the world has a choice — economic growth, fuelled by increasing energy consumption or a clean environment... . I believe there is a huge commercial prize for those who can offer better choices that transcend the tradeoff" [101].

Stuart Hart and Mark Milstein, of the Kenan-Flagler Business School at the University of North Carolina, note in *Sloan Management Review* that most of today's corporations evolved in an environment where energy and raw materials were cheap and abundant and sinks for waste disposal were limitless. But this environment is fast disappearing, due to concern about the ecological impacts of the technologies developed during this period. The authors argue that the emerging challenge of global sustainability will catalyze a new round of "creative destruction" — the economist Joseph Schumpeter's famous description of capitalism — that innovators and entrepreneurs will view as one of the biggest business opportunities in the history of commerce [102].

To grasp these opportunities, Hart and Milstein write, managers need to look beyond the continuous, incremental improvement of existing products and processes. The analogies with hydrogen and fuel cells — going beyond incremental improvements in the use of petroleum, the internal combustion engine, conventional power plants, and batteries — are evident, as are the commercial consequences. As Ballard President Firoz Rasul told carmakers at the 2001 Toronto Auto Show, "Your industry is undergoing a revolution brought about by fuel cell technology. The question you must ask yourself is: Are you a spectator or a player"? [102,103]

The geopolitics of energy will also be affected in fascinating but unpredictable ways. How will the Middle East, with significant remaining oil reserves but an enormous potential for solar hydrogen, fare in altering its source of energy exports? Former Saudi oil minister Sheik Yamani warns that, because of hydrogen and fuel cells, "a huge amount of oil…will be left in the ground", with potentially catastrophic consequences for oil producers that do not diversify into hydrogen. Will a hydrogen counterpart to OPEC emerge? Carl-Jochen Winter, organizer of the HYFORUM 2000 conference, has called for the creation of OHEC — the Organisation of Hydrogen Energy Utilizing Countries [104].

Another burning question is whether Asia, Latin America, and Africa, with their burgeoning mobility and power needs, can be persuaded and helped to bypass the hydrocarbon era that seemed to bring wealth, however short-lived and unsustainable, to the industrialized world. Will Eastern Europe withstand the petroleum temptations of the Caspian Sea region and consider an alternative, gas-based path? Is the United States, with former oilmen leading the government and promoting a "cheap-oil-forever" culture, destined to watch Europe and Japan become leading hydrogen producers and exporters, creating new jobs and revenue — with one of them, perhaps, succeeding America as the next great power? Or will Sacramento, home to the California Fuel

Cell Partnership and the end point of the 19th century's transcontinental railroad, be the starting point of the next great American network? [105].

In their 1999 book, *The Long Boom*, Peter Schwartz, Peter Leyden, and Joel Hyatt devote a chapter to the "Dawn of the Hydrogen Age", which argues that the achievement of the hydrogen age "will bring widespread repercussions, such as a geopolitical arrangement as Middle Eastern oil declines in importance. But the main consequence will involve the environment because hydrogen is so much more environmentally benign than its predecessors" [106].

The 20th century was, as historian J. R. McNeill has written, one of "ecological peculiarity", with mankind consuming more energy than in its entire previous history, launching an unprecedented experiment on the natural environment. But McNeill also warns of "ideological lock-in", with prevailing ideas and perspectives as to how the world works being slow to change. How strong is the ideological lock-in to hydrocarbon society, and will volatile fossil fuel prices, urban air crises, and climate change surprises break the lock? Can society successfully push government and industry along the cleaner hydrogen path? [107].

Public education may be the most needed and scarcest element of the hydrogen transition. T. Nejat Veziroglu, President of the International Association of Hydrogen Energy, notes that the "hydrogen energy movement" has made progress on many fronts over the last 25 years, in terms of the growing number of organizations, conferences, and scientific journals, and the rising political and commercial interest in hydrogen. The next stage of the movement will be to broaden the base beyond the "scientists, engineers, and dreamers" to whom Veziroglu refers, to include not only the politicians and businesspeople, but the general citizenry [108].

Several studies have been conducted in Germany which explore public understanding of hydrogen technologies. Gundi Dinse, of the Berlin-based Institute for Mobility Research, surveyed passengers on Munich's first transit hydrogen bus, pedestrians in Berlin, visitors to the 1999 Frankfurt Auto Show, and BMW employees. She found that hydrogen was generally accepted. But women, people with lower professional qualifications, and people over 60 tended to be more skeptical of the fuel [109].

Another study, prepared by German researchers for the European Commission, interviewed secondary school students and passengers in the Munich bus project. The study found a high level of acceptance of hydrogen technologies, support for their further development, and understanding of their environmental benefits. Though some danger of explosions was seen, people did not associate hydrogen with past accidents like the Hindenburg disaster. Acceptance of the technologies was higher among those who had direct contact with them — the bus passengers. However, general knowledge of hydrogen was relatively poor, and most people sought more information on the subject [110].

The greatest educational need today is to engage the public for input on the appropriate decisions to be made regarding fueling infrastructure. As Shell CEO Moody-Stuart told participants at HYFORUM 2000, "All of us want, if possible, to quickly introduce hydrogen technologies and reap their benefits, environmental and financial… . The popular perceptions of the risks involved in hydrogen technologies will have to be measured and addressed. A dialogue with all interested groups — everyone from national governments, to NGOs and customers themselves — will have to be stimulated and maintained. This is a vital process of introducing a new technology and it is an area in which cooperation is essential" [98].

Public pressure may in many cases be the prerequisite for the political leadership on hydrogen that is needed at all levels. As Bragi Árnason bluntly put it in discussing the origin of the Iceland initiative, "You must have the politicians". Indeed, when future historians document the history of the hydrogen economy, they will no doubt make special mention — perhaps with a nod to Jules Verne — of the scientific and political leadership of islands like Iceland, Vanuatu, and Hawaii — whose late US Senator Spark Matsunaga first promoted hydrogen in the 1970s. Matsunaga's legacy of leadership continues today in state Representative Hermina Morita, and in US Senator Daniel Akaka, who filled Matsunaga's seat after he passed away and is heading the reauthorization of the Hydrogen Future Act. The inspiration and example of figures such as these may help make public support for hydrogen as abundant as the fuel itself [111].

"There are risks and costs to a program of action", US President John F. Kennedy observed some four decades ago. "But they are far less than the long-range risks and costs of comfortable inaction". Kennedy's words were the product of a Cold War environment, but they are worth keeping in mind as we confront our increasingly urgent energy-related challenges. There are risks and costs involved in rapidly building a hydrogen economy, but they are far less than the long-range risks and costs of remaining comfortably committed to the hydrocarbon economy [112].

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