PERGAMON

International Journal of Hydrogen Energy 27 (2002) 235–264

International Journal of HYDROGEN ENERGY

www.elsevier.com/locate/ijhydene

Hydrogen futures: toward a sustainable energy system [☆]

Seth Dunn [*]

Worldwatch Institute, 1776 Massachusetts Avenue, NW Washington, DC 20036 1904, USA

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.

[☆] Printed with the permission of the Worldwatch Institute.

[*] Tel.: +1-202-452-1999; fax: +1-202-296-7365.

E-mail address: sdunn@worldwatch.org (S. Dunn).

0360-3199/02/$20.00 © 2002 International Association for Hydrogen Energy. Published by Elsevier Science Ltd. All rights reserved.
PII: S0360-3199(01)00131-8

"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, 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].

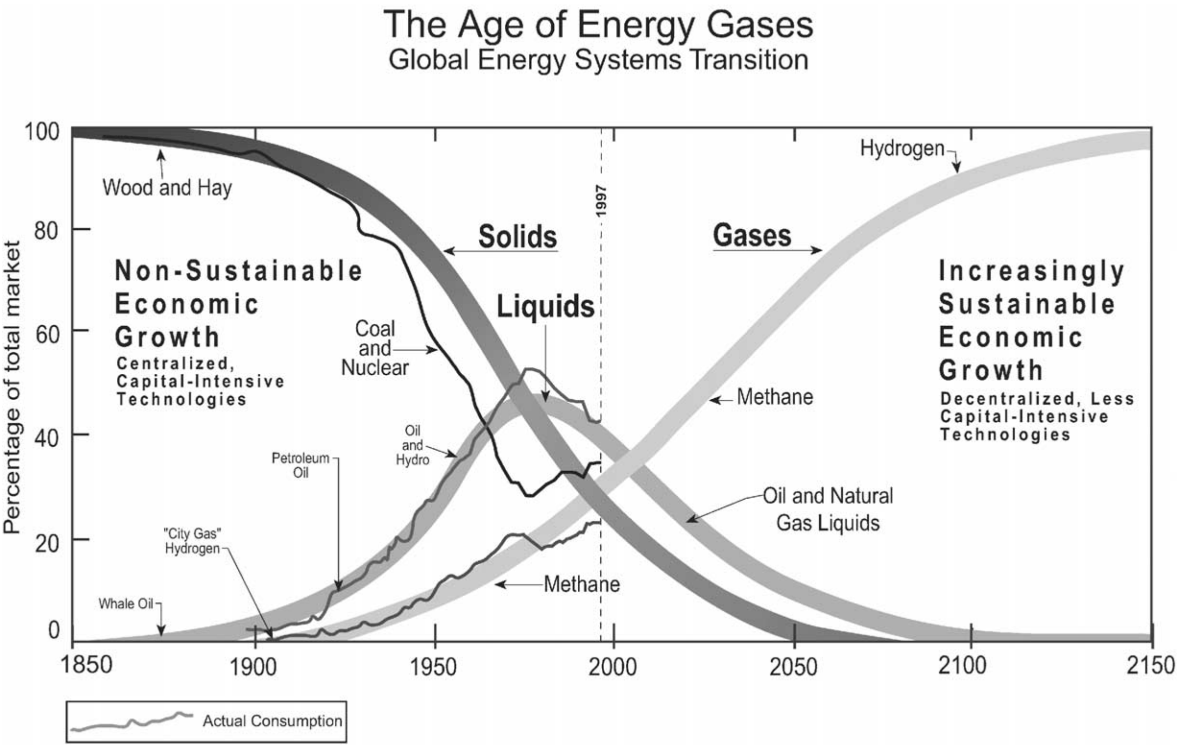


Fig. 1. Global energy systems transition, 1850–2150. Source: see [20].

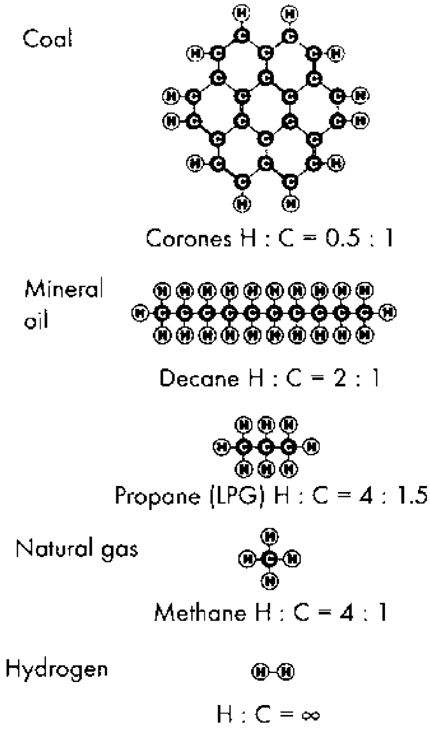
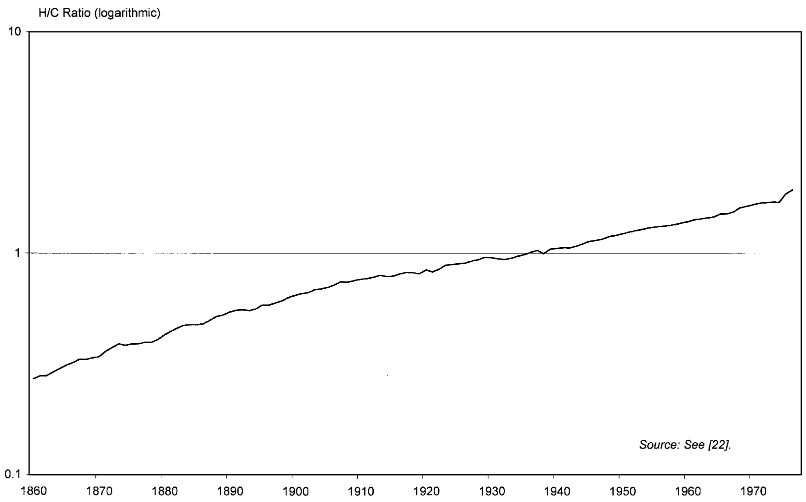


Fig. 2. The atomic hydrogen/carbon ratio. Source: see [22].



Source: See [22].

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].

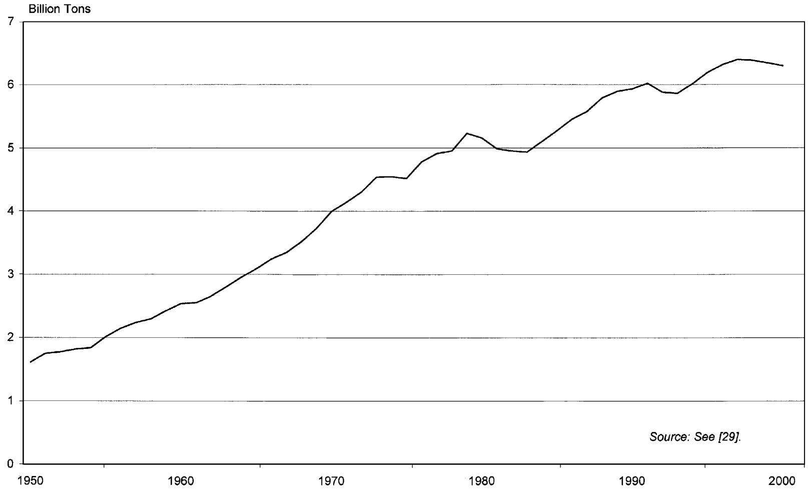


Fig. 4. World carbon emissions from fossil fuel burning, 1950–2000.

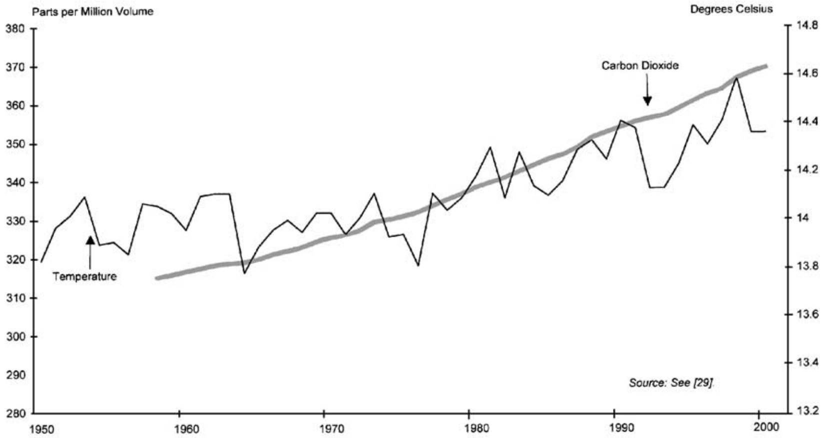


Fig. 5. Atmospheric carbon dioxide concentrations and global average surface temperature, 1950–2000.

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

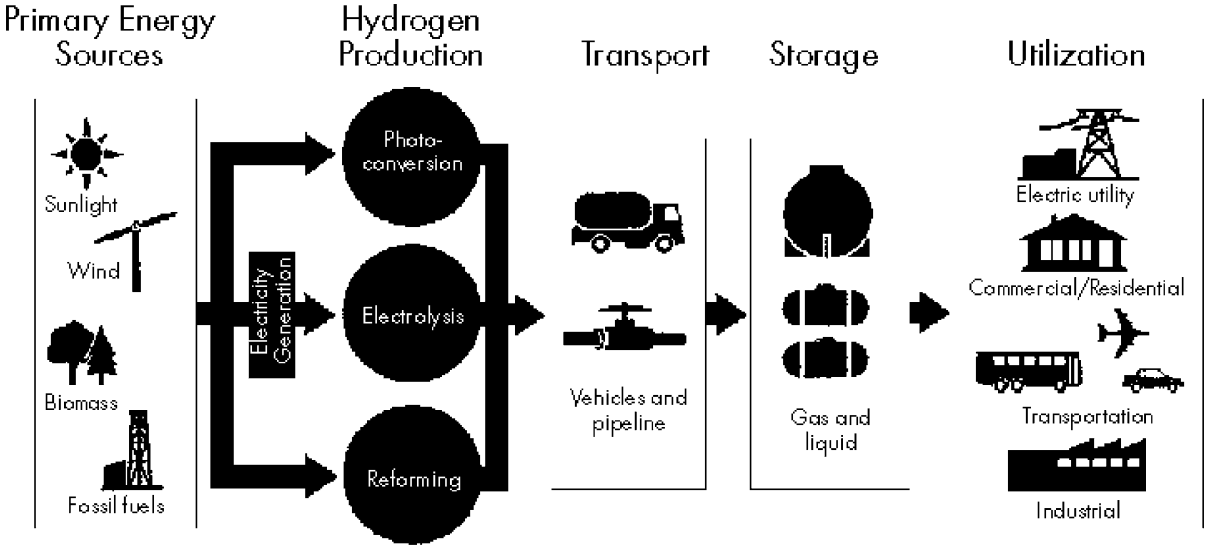


Fig. 6. A hydrogen energy system. Source: see [33].

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,

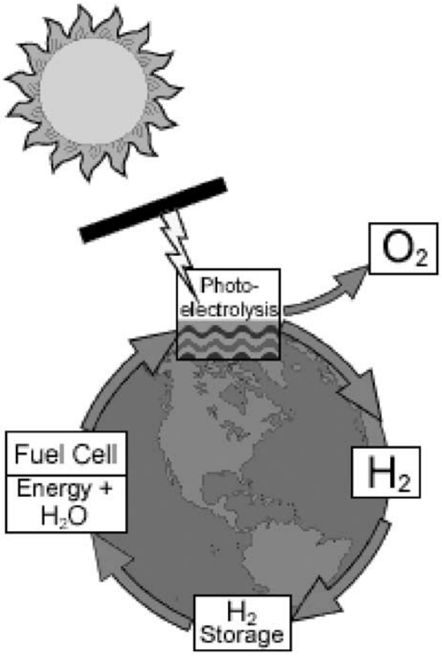


Fig. 7. A renewable hydrogen cycle. Source: see [40].

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].

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].

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].

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].

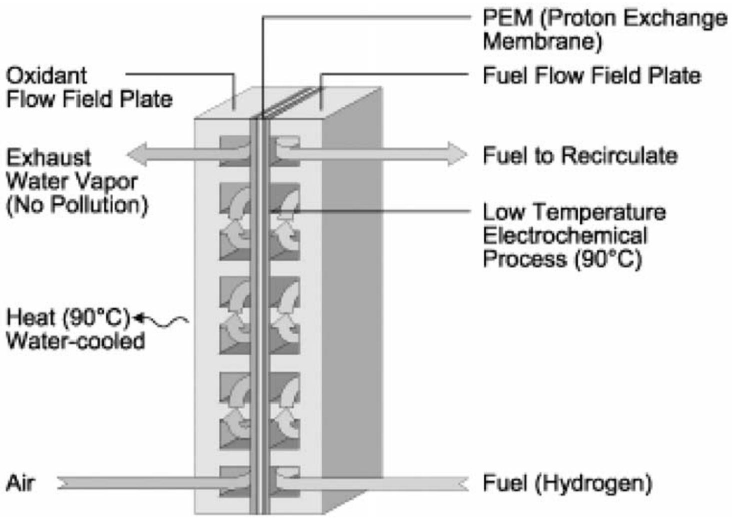


Fig. 8. A proton exchange membrane fuel cell. Source: see [53].

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