By Robert L. Olson

The Promise and Pitfalls of Hydrogen Energy

CHRIS EDWARDS / NATIONAL RENEWABLE ENERGY LABORATORY

Nonpolluting and renewable, hydrogen energy holds great promise as an energy alternative in the future. Here's a look at what's right about hydrogen energy—and how it can go wrong.

It's an exciting time for people involved with hydrogen, but it may also be a dangerous time. With money pouring in for R&D, a flurry of hydrogen workshops and conferences, and increased media attention, the hydrogen field is in the midst of a "bubble" somewhat like the Internet bubble of the 1990s.

Within a year or two, however, it will be clear that some of the business opportunities drawing attention from the private sector aren't as near term as they seemed. Today's overblown claims about how ready the technology is and how fast it can move will be exposed as uninformed. Some people will get disillusioned—and the hydrogen bubble will burst.

What happens then will depend on whether leaders in business and government understand hydrogen's long-term, strategic importance. Without this kind of long-term perspective, hydrogen development could stall.

We need to look beyond the usual planning horizons of business and government to see the enormous long-term benefits of moving toward a more hydrogen-based energy system. These benefits—which justify large, sustained increases in investment—only begin to appear over a decade and can't be fully realized until mid-century or beyond. If leaders appreciate what is possible over a 10- to 50-year period, then when today's hydrogen bubble bursts, it will be possible to settle into more-realistic, steady progress.

Hydrogen's Long-Term Benefits

A substitute for oil. Two-thirds of the 20 million barrels of oil consumed per day in the United States is used for transportation. Hydrogen is the best alternative for replacing that oil, which could be of critical importance sooner than later if gloomy forecasts of oil availability turn out to be right.

Many geologists project that within 10 to 20 years, oil production will no longer be able to keep pace with global demand. Optimistic analysts argue that we will not reach this point until after 2030; pessimists warn that it could happen before this decade is over. Extracting oil from deep-sea regions, tar sands, and oil shale could offset the shortfall for a time, but experts debate how large a role these sources should play because they will be expensive and environmentally damaging.

Given these disagreements and the uncertainties involved, strategic planners at companies such as Royal Dutch Shell and British Petroleum Co. Ltd. are concluding that the time has come to create new corporate divisions devoted to hydrogen as a substitute for oil and to start making major investments.

Security benefits. Even if the peak and decline of global oil production is decades away, developing hydrogen's potential is important for national and global security.

The turmoil in Iraq has once again focused attention on the world's growing dependence on oil from the volatile Persian Gulf region. The United States, for example, imported 54% of its petroleum supply in 2001, almost a quarter of it from the Persian Gulf. By 2020, the United States will import 70% or more of its oil, the U.S. Department of Energy projects. Between now and then, the output of smaller producers will decline and we will become increasingly dependent on a small number of nations with the largest reserves—nations that may include Saudi Arabia, Iraq, Iran, the United Arab Emirates, Kuwait, and Libya.

Given the vital importance of oil to the world economy, the instability of the Persian Gulf region, and hostility toward the United States among populations in the region, this projected level of import dependence should be considered an intolerable security risk. Hydrogen development can reduce that risk because hydrogen can be produced from a wide variety of domestically available resources: natural gas, biomass, wind, hydroelectric, solar, coal, and nuclear.

Cost-effective electrical generation. Fuel cells and other micropower sources, collectively called *distributed generation,* will likely emerge as the most economical approach to providing new electrical generating capacity. Micropower on site or feeding a local grid eliminates the cost of distributing power, and in large utility grids most of the cost is actually in transmitting the power rather than in generating it. On-site and local-scale power eliminates grid losses and makes it possible to harness waste heat for heating and cooling.

Environmental benefits. Energy production and use is arguably the largest single source of environmental degradation. Environmental impacts include multi-pollutant urban air emissions, regional acid rain, and global warming. By contrast, the only emission from fuel cells running on hydrogen is pure water.

The greatest potential environmental benefit is that hydrogen technologies can reduce and eventually eliminate today's massive releases of carbon dioxide from fossil-fuel combustion. These emissions are the main driver of global warming.

But how clean hydrogen really is depends on how it is produced. Energy is required to produce elemental hydrogen, and if that energy comes from fossil fuels there will still be emissions, including releases of carbon dioxide. The priority our society gives to minimizing climate change will be a major factor determining what kind of hydrogen economy we create.

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General Motors' HydroGen3, the first fuel cell vehicle to be commercially tested, is on Japanese streets from 2003 to 2004 as part of a joint GM–Federal Express program to advance fuel cell technology.

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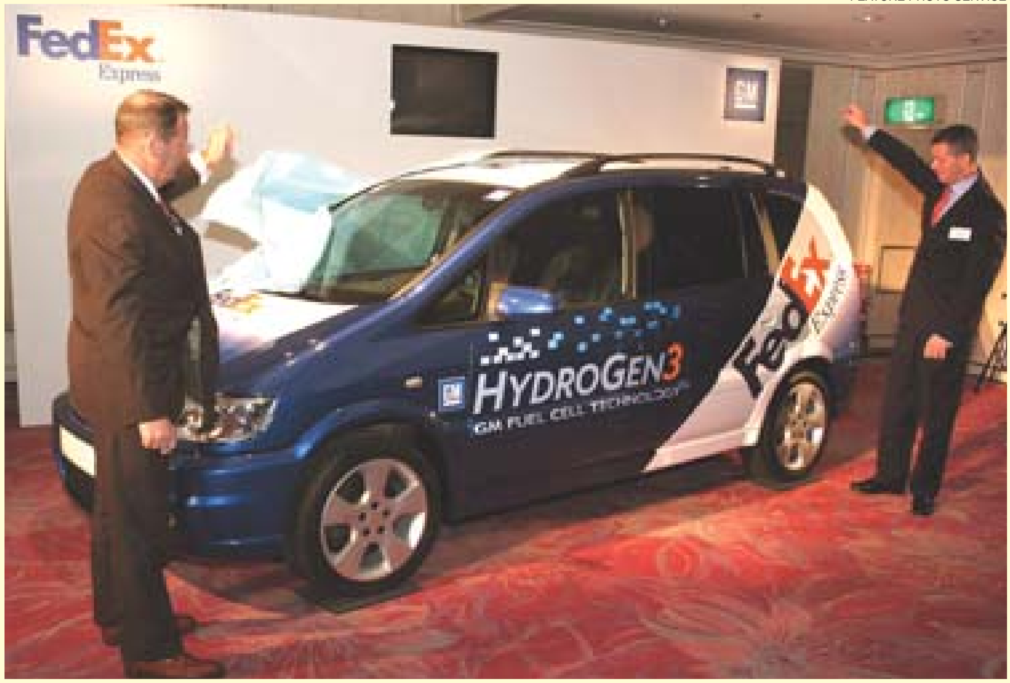

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Computer-generated model of a hydrogen refueling system by Proton Energy Systems Inc., which makes industrial hydrogen generators (electrolyzers) and fuel cell products.

CURTIS BOLES / OAK RIDGE NATIONAL LABORATORY

Researcher Eli Greenbaum studies algae in an illuminated flask. Greenbaum's work aims to use algae to produce hydrogen from water.

Reliable, renewable energy. One of the biggest disadvantages of solar and wind power is their intermittent nature. The sun rises and sets, the wind gusts and calms. Power is not always generated at the times and places where it is needed, and none of today's energy storage technologies is versatile enough to be widely used for storing electricity on a large scale. However, by using renewable energy to produce hydrogen, the hydrogen becomes a storage medium and a "renewable energy carrier" that overcomes these problems.

Renewable energy technologies, like hydrogen itself, will take decades to put into place on a large scale. In the near term, the cheapest way to produce hydrogen is by reforming natural gas. Because natural gas is the cleanest fossil fuel, it is likely to play a major transitional role even if renewable energy technologies eventually come to dominate electricity and hydrogen production.

Sustainable global development. Today's industrial nations were able to base their development on cheap oil. That option is unlikely to remain available for very long to the world's developing nations. Oil will become more expensive over the decades ahead, and global warming may force us to move away from oil long before reserves are depleted. Hydrogen technologies can allow developing nations to move toward U.S. and European levels of affluence without depleting resources or compromising the environment.

Achieving this vision will require further progress and cost reduction in hydrogen production, storage, distribution, and conversion. But no technological showstoppers appear to stand in the way. Hydrogen produced from a wide variety of sources, and ultimately perhaps from just sunlight and water, should be able to sustain economic activity and personal mobility indefinitely.

How Things Could Go Wrong: Three Negative Scenarios

Unfortunately, there is a very real possibility that society will fail to achieve many of these benefits. The three negative scenarios below illustrate how things could go wrong.

Negative Scenario 1: Faltering Support. When today's exaggerated expectations are not realized, political support for hydrogen may falter. Government budget cuts could be crippling to companies that have invested heavily in hydrogen R&D with hopes of profits down the road. Some of the most innovative companies are already struggling in the current climate of economic uncertainty and falling stock prices.

Ironically, the chances that hydrogen will lose political support are increased by some of the United States' own efforts to promote it. Increased R&D funding to develop hydrogen fuel cell cars over the long run was accompanied by an abandonment of R&D aimed at making cars cleaner and more fuel-efficient in the short run. Some environmental groups thus denounced hydrogen R&D programs as a "dirty energy plan" because much of the research is focused on ways to produce hydrogen from gasoline, coal, and nuclear power.

Environmentalists could be further angered if expanding fuel cell production produces new pollution and waste-disposal problems. So far, little attention has been given to applying "design for the environment" principles to fuel cell manufacturing in order to design out environmental problems early on. Political and consumer support for hydrogen could also weaken if accidents involving hydrogen begin to make the headlines.

If support for hydrogen falters, hydrogen would not be ready as a substitute for oil once global oil demand exceeds supply. Oil prices would increase and might reach levels that trigger a global energy crisis with severe, long-term economic impacts.

Negative Scenario 2: Premature Lock-In. Another way hydrogen development could go wrong is through a premature commitment to technologies that could soon be supplanted by better ones. Developing markets sometimes lock-in early on inferior designs, as happened when the awkward QWERTY keyboard format achieved a virtual monopoly, or when VHS achieved dominance over Betamax in the VCR market.

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There are several ways this kind of premature lock-in could happen in hydrogen development. The most hotly debated possibility involves the question of whether an initial generation of hydrogen fuel cell cars should be designed to run on gasoline. Several oil companies and automobile manufacturers have favored this approach, and it has benefited from heavy government R&D support. It involves building cars with onboard fuel processors to reform gasoline to hydrogen. The great advantage of this strategy is that it allows fuel cell cars to piggyback on the existing gasoline production and distribution infrastructure, avoiding the time and financial risks involved in building a new hydrogen infrastructure. It could allow fuel cell cars to come into the market sooner than would otherwise be possible.

Critics argue that this attempt to make a fast start on fuel cell cars will slow investment in creating a hydrogen infrastructure, causing a false start for the hydrogen transition as a whole. They point to studies suggesting that cars using onboard fuel processors are likely to be expensive and inefficient, with no advantages over fuel–electric hybrids. If fuel cells and reformers are too expensive, they are likely to fail in the marketplace and give fuel cell cars a bad reputation.

On the other hand, critics worry that if cars with onboard fuel processors do succeed in the marketplace, the auto market could lock-in on them for decades, denying society the benefits of more-advanced cars that run directly on hydrogen. Direct hydrogen vehicles would cut dependence on imported oil, improve vehicle energy efficiency, and completely eliminate exhaust and carbon-dioxide emissions. Most importantly, using direct hydrogen would decouple energy sources from the vehicles themselves, giving vehicles the flexibility to run on hydrogen produced from a variety of domestic resources.

Negative Scenario 3: Undesirable Hydrogen Infrastructures. There are many ways in which a hydrogen infrastructure with highly undesirable consequences might be created. Suppose, for example, that hydrogen development focuses on reforming hydrogen from natural gas and coal. This could happen if renewable energy (solar, wind) is never able to compete effectively against heavily subsidized fossil fuels and if nuclear power remains blocked by investor wariness and public opposition. Suppose, further, that technologies for capturing and sequestering the carbon dioxide produced in reforming natural gas and coal prove too expensive for widespread use. Then hydrogen development might make it possible to move away from oil toward gas and coal—but growing carbon-dioxide emissions would continue to drive global warming.

Many people involved in hydrogen believe the long-term "home run" of hydrogen development would be an energy-efficient economy based on hydrogen extracted from water using solar energy.

Another potential problem: Public demand for sharp reductions in fossil-fuel burning could open the door to a global revival of nuclear power. This kind of shift in public opinion is possible if, as many climate models predict, the next few decades bring higher sea levels, more extreme weather events, and costly impacts on water resources, coastal development, and agriculture. Nuclear energy is the one mature technology able to produce both hydrogen and electricity with no greenhouse-gas emissions.

But deploying nuclear power globally on a massive scale would take us toward a future where tens of thousands of bombs' worth of nuclear materials are being produced, enriched, reprocessed, and shipped around the world every year. Given the growing dangers of nuclear proliferation and terrorism, is that a future we really want to create?

If Things Go Right: Four Positive Scenarios

Positive Scenario 1: Full Spectrum Development. One route to a positive future involves continuing to provide R&D support for fuel cells, but focusing less on using them in cars and more on using them for generating electricity. This is a sensible business strategy because fuel cells will move into power-generation markets over the years just ahead, but fuel cell costs will need to drop considerably to be viable for widespread use in cars. That will probably take 15 years or more.

Developing large-scale fuel cell manufacturing operations for power markets is the best strategy for bringing fuel cell costs down to where they become practical for use in cars. While power markets are being developed, automobile manufacturers could follow a path being pioneered by BMW and Ford and produce internal combustion engines modified to run on hydrogen. Although not pollution free, these engines have much lower emissions than conventional gasoline engines and require no major retooling in the auto industry. This approach would quickly increase the demand for hydrogen, accelerating the development of a hydrogen infrastructure.

As demand for hydrogen grows, the central question of hydrogen development will be how best to produce it. Reforming hydrogen from natural gas is the most economical option now, and will be for some time, but governments and energy companies are already beginning to invest in developing more cost-effective ways to produce hydrogen from biomass, coal, nuclear power, solar, and other forms of renewable energy. Developing the full spectrum of potential hydrogen sources keeps options open and elicits support from all parts of the energy industry. Parallel investments in methods to capture and sequester carbon dioxide are essential in this kind of scenario so that the full range of fossil fuel sources can be used in a climatically benign way.

The major risk in this approach is making investments for political reasons rather than on the basis of objective assessments. Newer hydrogen production options using renewable energy could get less financial support than those championed by powerful, mature industries like oil, coal, and nuclear.

Positive Scenario 2: Solar Hydrogen. Many people involved in hydrogen believe the long-term "home run" of hydrogen development would be an energy-efficient economy based on hydrogen extracted from water using solar energy. They think that if this kind of hydrogen development path proves possible it would be best for the environment, best for national and global security, and best for sustainable global development.

The hope is that a solar hydrogen future will emerge from a full spectrum development approach where objective assessments of the full costs and benefits of different options guide investments. Wind power is already becoming competitive with coal. Solar electricity costs will fall sharply over the next few years as thin-film materials replace rigid silicon disks in photovoltaic systems. Major corporations like General Electric and BP are investing heavily in wind and photovoltaic systems with an eye not only to markets in industrial nations but also to the 2 billion people in developing countries without electric power. And a number of the entrepreneurs and venture capitalists who made fortunes in the high-tech boom of the 1990s are now convinced that renewable energy, combined with hydrogen, is "the next big thing"—a disruptive technology that will transform entire industries.

The Excitement about Hydrogen

Skyrocketing interest in hydrogen has spurred a frenzy of big-money R&D initiatives. More than a hundred companies are racing to commercialize hydrogen fuel cells for a range of applications, from generating electric power to running small devices like cell phones. And in the automobile industry, the race to the marketplace is especially heated.

Ford, General Motors, and DaimlerChrysler have already spent over $2 billion developing fuel cell vehicles. Honda and Toyota were first on the road with small demonstration fleets of fuel cell vehicles already operating in Japan and California. GM has just begun a fleet demonstration program in Washington, D.C.; to fuel them, Shell will open the first U.S. commercial hydrogen refueling station in Washington this October. Other companies, such as Nissan, Mitsubishi, Peugeot, and Renault, are working hard to catch up.

Governments are also pouring funds into the hydrogen field. U.S. President George W. Bush recently committed to spending $1.7 billion on hydrogen over five years; meanwhile, the U.S. Department of Energy has carried out a reorganization to elevate the status of its hydrogen-related work. Between them, nations in Europe spent nearly $200 million on fuel cells and hydrogen in 2001 alone, and European Union member states, plus Iceland and Norway, have initiated an integrated study of hydrogen options called Hy-Society. Japan's WE-NET hydrogen program is targeted for $11 billion in funding between now and 2020.

Why All the Excitement?

Recent progress in fuel cells—the key hydrogen technology—is the main development attracting attention to hydrogen today. Fuel cells convert hydrogen to electricity without combustion, using an electrochemical process that is highly efficient and totally nonpolluting. The hydrogen for fuel cells can be "reformed" (extracted or converted) from hydrocarbon fuels like oil, natural gas, and coal or produced by splitting water into hydrogen and oxygen.

In the 1960s and 1970s, power produced by fuel cells cost $600,000 per kilowatt. Today, United Technology Corporation's PC 25 fuel cells are finding a number of niche market applications at $4,500 per kilowatt. And forecasts show the costs will continue to drop dramatically:

- Fuel cells coming on the market in late 2003 and 2004 are expected to cost $1,200 to $1,500 per kilowatt, which would make them competitive with diesel generators.
- The next generation of fuel cells now in the labs is expected to cost less than $1,000 per kilowatt, which would make these cells competitive for utility-level power generation.
- By the end of this decade, fuel cells are expected to cost about $400 per kilowatt, which would make them competitive with every type of power.

The further costs fall, the more production will increase, and economies of mass production will bring costs down still further. The bottom line: Fuel cells and other hydrogen technologies are going to break out into the marketplace during the next two decades.

—Robert L. Olson

A solar hydrogen economy is much more likely to emerge if governments help drive demand and spur innovation. The state-level practice of setting goals for energy generation from renewable sources could spread throughout the United States. Government-organized markets for trading in carbon would promote investment in energy efficiency as well as renewable energy. Well-targeted increases in R&D funding could spur progress in critical areas such as improving the efficiency of photovoltaic cells and reducing the cost of electrolyzers for hydrogen production.

The danger in this approach is that solar technologies may not perform as well, technically and economically, as their proponents hope. That concern justifies keeping other hydrogen production options open, even if solar hydrogen looks increasingly attractive.

Positive Scenario 3: Apollo Project for Hydrogen. Senator Byron Dorgan (Democrat, North Dakota) wants "an Apollo-type initiative" and has introduced legislation supporting a $6.5-billion, 10-year plan. However, an effort really equivalent to the Apollo Project would mean spending about $100 billion in today's dollars over a decade. Yet given the full range of hydrogen's benefits—liberating the United States from oil dependence, preserving personal mobility, reducing air pollution, stemming global warming, and providing a foundation for sustainable global development—can it be argued that investment on this scale is not worthwhile?

What makes an effort this large plausible is that most of the technical challenges involved only require engineering improvements, not scientific breakthroughs. That means spending more money can bring faster progress.

What makes an effort like this problematic is the difficulty of making wise investments quickly when we still lack agreement on the best technical path forward. A slower effort, on a similar scale, with more pilot projects, more careful assessments of benefits and costs, and more opportunities to test alternative

Hydrogen from Plants

Almost half of hydrogen produced worldwide today is made from natural gas, while heavy oils and naphtha account for 30%, coal another 18%, and wind/electrolysis another 4%, according to *The Carbohydrate Economy,* a publication of the Institute for Local Self-Reliance. However, there's another renewable source by which to obtain hydrogen: biomass, or plant matter.

Because biomass typically contains only about 6% hydrogen, some argue it's not a viable source of hydrogen. But with steam reforming—which uses heat to split off the hydrogen in the water and free the hydrogen in the biomass—about 50% more hydrogen can be harvested.

From each metric ton of dry biomass, about 66 kilograms (145.5 pounds) of hydrogen is produced—the energy equivalent of 74 gallons of gasoline. It would take about three tons of dry biomass to fuel a year of driving—roughly 12,000 miles—in fuel cell cars that get the equivalent of about 60 miles to the gallon.

In terms of renewable sources, the advantage of biomass over wind is that it's more controllable, which means it can be designed to more closely match production to demand. Unlike wind, however, it can't use the existing electrical grid to transport energy for hydrogen production. Thus, both biomass and wind would be needed to produce a significant amount of hydrogen from renewable sources.

Source: *The Carbohydrate Economy* (Winter 2003); www.carbohydrateeconomy.org.

approaches in the marketplace might bring better results.

Positive Scenario 4: Technology Transformation. Technological developments outside the hydrogen field could actually enhance hydrogen's promise. For example, progress in the development of nanomaterials could lead to improved membranes and catalysts that make fuel cells cheaper and more efficient. Nanomaterials could also revolutionize hydrogen storage, making it possible to produce advanced hydrogen absorbents and strong, lightweight tanks to safely store highly compressed gas. Tiny embedded sensors for detecting stresses and leaks could improve hydrogen safety. Nanorod solar cells made from electrically conductive polymers shot through with nanoscale semiconducting crystals could prove as efficient as the best of the old silicon-based solar cells, but dirt cheap. They could be rolled out like plastic wrap, ink-jet printed, or even painted onto surfaces.

New options are likely to become available for producing hydrogen. Photoelectrochemical-based water-splitting systems could produce hydrogen directly from sunlight and water. Biological dissemblers could replace older technologies for extracting hydrogen from biomass wastes. Bioreactors could produce hydrogen using bacteria and algae that have been modified chemically, physiologically, and genetically to maximum production efficiency.

Looking back from 2030 at the polluting, resource-depleting, and nuclear proliferation-prone energy systems of the late twentieth century, people may find it hard to imagine how anyone could have seriously believed that these were "advanced technologies."

Strategic Conversations About Hydrogen

Scenarios like these could be developed more systematically, and there are other images of the hydrogen future that are equally plausible. Yet the actual future is unlikely to be exactly like any of them. Scenarios don't predict the future; they are merely tools for thinking more clearly and creatively in situations where the future is unpredictable. Good scenarios provide an intellectual framework and a common vocabulary for strategic conversations.

Business and government leaders involved in hydrogen development need to engage in strategic conversations about the long-term big picture of alternative paths and key choices ahead. Among the questions these leaders should tackle: What are the different plausible scenarios of pathways toward a hydrogen future? How can we assess which paths are likely to be least expensive, best for the environment, and most adaptive to technological change? What can business and government do to avoid locking in prematurely on technologies and paths forward that could soon be supplanted by better ones? Without exploring questions like these and assessing the pros and cons of a wide range of scenarios, we might create a hydrogen future that fails to give us many of the benefits that make hydrogen so attractive.

The key to moving beyond today's hydrogen bubble is to develop a widely shared long-term perspective on the enormous benefits that hydrogen development can provide. And the key to achieving those benefits is to develop a long-term perspective on the alternative paths ahead and the kind of future we really want to create. □

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