The Hydrogen

LAYING OUT THE GROUNDWORK

Richard G. Newell

In the 1970s, several studies predicted a hydrogen fuel economy might emerge as early as the year 2000. Flash to the present—where, in his 2003 State of the Union address, President Bush put forward the Hydrogen Initiative, which would involve spending $1.2 billion over five years to develop hydrogen, fuel cell, and infrastructure technologies to reduce our dependence on foreign oil. His goal is to make it possible for enough Americans to choose hydrogen fuel cell vehicles by 2020, so that, as the president put it, "the first car driven by a child born today could be powered by hydrogen."

More recently, California Governor Schwarzenegger set out his Hydrogen Highway goal of building, by 2010, a network of 150–200 hydrogen fueling stations throughout the state, making hydrogen fuel available to a majority of Californians. Meanwhile, hydrogen-fueled demonstration vehicles and related filling stations are making news in the nation's capital.

So what's all the buzz about? In addition to being a potential substitute for oil, hydrogen use in fuel cells is pollution-free, thereby eliminating emissions that cause air quality problems. The impact on carbon dioxide emissions and global climate change depends on how the hydrogen itself is produced—whether it is from nuclear or renewable energy sources or from fossil fuels—and what is done with the emissions generated by its production. Potentially, a "hydrogen economy" could evolve that addresses both the energy security and environmental concerns associated with our current "carbon economy."

Significant scientific and practical hurdles must be surmounted before hydrogen becomes a cost-effective part of the energy system, however. These hurdles extend from the initial production of hydrogen, to its distribution and storage, and through to the final conversion of hydrogen into energy through fuel cells or other means. A reasonable person might ask, "In 20 years, will we be reading again that the hydrogen economy is only 20 years away?" To shed some light on this question, this essay briefly reviews the challenges to the widespread hydrogen use in light-duty vehicles and offers some perspective on the likely timeframe in which they might be overcome.

Hydrogen production

About nine million tons of hydrogen are produced per year in the United States, with about one-third used in the manufacture of ammonia and most of the remainder in petroleum refining. A recent National Research Council (NRC) report suggested that under an optimistic timetable, hydrogen-fueled vehicles could replace light-duty vehicles by 2050. But that would require about 111 million tons of hydrogen per year—more than 12 times current production levels. For this to be a plausible and desirable future, at least two major production challenges must be met: cost and climate friendliness.

Economy

Hydrogen gas does not exist naturally on earth as an isolated element. Rather, it must be produced by chemically separating it from other elements, particularly carbon and oxygen. One way to do this is through electrolysis, whereby hydrogen is separated from the oxygen in water, producing water vapor and heat as the only by-products. This process is simple, but it is also very expensive because the electricity that drives the process must itself be generated. At current electricity prices, producing hydrogen through electrolysis costs about seven times more than gasoline per unit of usable energy. Hydrogen production using electricity generated from renewable sources, such as wind, solar, and biomass, faces the same cost disadvantage of those options in producing electricity but emits little or no carbon dioxide.

If hydrogen-fueled cars are ever going to make it, hydrogen must at some point be widely available to consumers—this quintessential chicken-and-egg problem is what has gotten policymakers' attention.

Currently, fossil fuels containing both carbon and hydrogen are used to produce hydrogen. Natural gas is the most common feedstock, through a relatively cost-effective process known as catalytic steam reforming. Hydrogen produced from natural gas is much cheaper than electrolysis-based hydrogen but still presents a significant cost barrier, being about two to four times the price of gasoline per unit of usable energy. Also, if the price and amount of natural gas imported continues to increase, its desirability as a method of producing hydrogen will decrease.

Another concern about hydrogen from fossil fuels is the stream of carbon dioxide released as a by-product. While the NRC hydrogen report finds that many of the possible future supply chains would release significantly less carbon dioxide than hybrid gasoline-electric vehicles, the least expensive options based on natural gas and coal still emit significant amounts. Therefore, if hydrogen is to be produced from fossil fuels in a climate-friendly manner, it will need to be coupled with carbon emissions capture and storage. This is technically feasible but currently very expensive (at least $50 per ton of carbon dioxide) and faces its own technical, political, and environmental challenges if it is to help mitigate the climate problem.

Coal is also used in much smaller amounts for current hydrogen production but it could be a key feedstock in the future, given its widespread domestic availability. But coal contains the most carbon dioxide per unit of energy. In response to this environmental challenge, the Department of Energy set up a 10-year, $1 billion program (known as FutureGen) to research producing hydrogen cost-effectively through integrated gasification combined-cycle (IGCC) plants for electricity production and other uses, and storing the resulting carbon dioxide emissions underground.

Nuclear-based hydrogen production is also a possibility, through either electrolysis or more speculative high-temperature thermochemical processes. Nuclear-based hydrogen has the advantage of generating no carbon dioxide emissions but also the usual safety, security, and cost disadvantages of nuclear power. Other innovative (but currently very expensive) approaches include photochemically producing hydrogen using algae, sunlight, and catalysts to split water molecules directly.

Hydrogen distribution

The next link in the hydrogen economy chain is developing the necessary infrastructure for distributing hydrogen from production sites to fueling stations and storing it there. Because of its very low density and high flammability, hydrogen presents unique cost, safety, and convenience challenges at every step. But if hydrogen-fueled cars are ever going to make it, hydrogen must at some point be widely available to consumers. This quintessential chicken-and-egg problem is what has gotten the attention of policymakers, including the president and the governor of California.

> **A major technical challenge of widespread hydrogen use is safely storing adequate quantities onboard vehicles. As the lightest element, it takes up far more space than other fuels, even when compressed.**

A big question is whether hydrogen should be produced at central facilities and distributed as molecular hydrogen for end use or at smaller facilities located directly at filling stations. This involves a trade-off between economies of scale in centralized production and the cost and safety of a transportation infrastructure, which would be less necessary with distributed generation of hydrogen. In the long term, the NRC report predicts that the most economic approach will likely be large-scale centralized generation with pipeline distribution.

Under this scenario, the cost of distributing the hydrogen is expected to be approximately equal to the cost of producing it. In the interim, however, distributed generation using small-scale natural gas reformers or electrolysis is more feasible and is likely to be a necessary part of any transition. Transport of low-temperature liquid hydrogen via trucks or rail could also play a significant role. If hydrogen were distributed as part of a chemical compound, a whole different system would be required. All of these options face significant technical and economic hurdles.

Onboard hydrogen storage

Perhaps the biggest technical challenge facing widespread use of hydrogen is safely storing adequate quantities onboard vehicles. As the lightest element, hydrogen takes up far more space than other fuels, even when compressed. With current technology, enough compressed hydrogen gas to move a car about 300 miles takes up about four times as much space as a typical gas tank. Liquefying hydrogen can reduce its volume several times, but that requires chilling it to minus 253°C, taking up to 30 percent of the hydrogen's energy to do so and using larger insulated tanks to maintain this low temperature. Currently, most experts are skeptical that onboard hydrogen storage in a gas or liquid form can meet the capacity, size, and safety requirements of the automotive industry.

Advanced materials for "solid-state" storage are also under investigation, including metal hydrides and carbon nanotubes. These options typically involve adsorbing—or coating materials with a thin layer of a substance—the hydrogen into the advanced materials and later releasing it when needed for driving. Each of these options faces serious technical obstacles, however, requiring further research and development. In addition to these concerns, an acceptable storage system must be capable of being refueled within just a few minutes, be safe, and be reliable over the decade-plus lifetime of a car. Even if technical problems can be met, there is still the issue of cost.

Hydrogen use

The final piece of the hydrogen puzzle is the conversion of hydrogen into useful energy through fuel cells or advanced internal-combustion engines. While fuel cells were invented well over a century ago and have been successful on spacecraft for decades, the current cost of power from them is about 100 times higher than from internal-combustion engines. Some estimates place the potential price of a fuel-cell vehicle at over $1 million, with the fuel cell and storage tank contributing most of the cost. Other challenges include durability of fuel cells under continuous vibration and consistency of operation under different conditions. It took about 20 years for wind and solar power to see tenfold declines in cost, and current penetration of these technologies is still under 1 percent of electricity generation.

Some automakers are also pursuing the alternative course of developing internal-combustion engines that run on hydrogen instead of gasoline, at least as a transition technology to hydrogen fuel cells. This course would not require the parallel creation of an economic fuel-cell car and a hydrogen infrastructure, but still would require facing the hydrogen infrastructure as a major stumbling block. While such engines do face technical hurdles, they are not typically thought to be as great as for the fuel cell. On the other hand, these engines would still produce small amounts of nitrogen oxides and would not be as efficient in converting hydrogen to useful energy as are fuel cells.

Conclusion

Widespread, cost-effective use of hydrogen will come only when the very large cost and technical barriers that now exist are removed. Each aspect of the hydrogen system—from production, to distribution, storage, and use—faces a cost disadvantage several times that of competitive alternatives. But the negative security and environmental consequences of petroleum use, and the dearth of attractive alternatives, make further research into hydrogen's potential absolutely essential.

Many of the most pressing questions surrounding the hydrogen economy are still largely technical at this time. Economics will play an increasing role, however, if and when these questions get resolved and hydrogen moves toward a commercially viable fuel choice.

Given the magnitude and complexity of the challenges that lie ahead for hydrogen, successful resolution will probably take several decades, not 15 years as the president predicted. Now is not the time to close out options or focus too much on deployment due to near-term policy goals and political pressures, but rather to explore a wide range of options, many of which may not pay off in the end. And in the interim, more effort and more funding need to go toward reducing petroleum use by advancing the development of new gas-electric hybrids, advanced diesel-fueled vehicles, and the like. ■