Hydrogen Highways: Lessons on the Energy Technology-Policy Interface

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The hydrogen economy has received increasing attention recently. Common reasons cited for investigating hydrogen energy options are improved energy security, reduced environmental impacts, and its contribution to a transition to sustainable energy sources. In anticipation of these benefits, national and local initiatives have been launched in the United States, creating pilot "roadmaps" and technology partnerships to explore hydrogen economy platforms. Although hydrogen can provide several positive improvements over a carbon- or uranium-based energy system, several problems are also likely. As well, competitive technologies (e.g., hybrid vehicles) may offer comparatively greater economic and/or environmental advantages. Before policies to advance a hydrogen energy economy proceed, it is vital that all aspects of hydrogen be compared with other available alternatives. Important questions to ask in this regard are whether a hydrogen economy can fulfill key energy needs and whether there are appropriate roles for hydrogen to play in a sustainable energy future.

Keywords: *hydrogen; energy policy; sustainable energy; hydrogen scenarios*

Defining the Hydrogen Economy

The hydrogen economy is not simply a proposal for a change in fuel mix. It entails the development and diffusion of a set of technologies that use hydrogen to carry energy from conventional or alternative energy sources to various end uses. Hydrogen is an energy carrier, not an energy source, and acts as a medium of storage and transmission of energy from other sources. When combined with a fuel cell, hydrogen can provide electrical power and replace primary fuels such as gasoline. Energy from fossil or renewable sources is converted to hydrogen either by using electricity from these sources to split water into oxygen and hydrogen (in a process known as electrolysis) or by removing hydrogen from a feedstock (usually natural gas) and using its energy value.

There are many pathways along which a hydrogen economy could develop, and each would have different effects on the environment, the economy, and energy security. Currently, the reformation of natural gas is considered to be the dominant pathway for the near and intermediate future for producing hydrogen gas (National Academies of Science [NAS], 2004; Ogden, 1999). Natural gas is dominant for several reasons. New infrastructure needed to produce hydrogen from natural gas would be moderate. A large infrastructure for the distribution and extraction of natural gas already exists and more than 90% of the hydrogen produced in the United States for industrial purposes is derived from steam reformation of natural gas (Ogden, 1999, p. 239). The amount of hydrogen necessary during the early stages of the hydrogen economy could be relatively easily produced by the existing natural gas infrastructure (NAS, 2004).

Natural gas yields the greatest hydrogen-to-carbon dioxide ratio of all the fossil fuels. When it is reformed into hydrogen and used in a fuel cell vehicle, carbon dioxide emissions drop by more than 60% compared with a gasoline internal combustion engine. If natural gas is reformed in a central location, sequestration of the resulting carbon dioxide may reduce overall emissions by an additional 20% compared with gasoline (NAS, 2004). Other methods

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by which hydrogen may be produced are gasification and then reformation of liquid and solid fossil fuels, the electrolysis of water, biomass conversion, and some experimental methods involving the direct photoelectric splitting of water and production via algae or bacteria. Only hydrogen derived from electrolysis powered by renewable energy would result in a significant reduction of carbon emissions over steam reformation of natural gas.

In terms of economics, hydrogen from natural gas is 50% to 100% more expensive than an equivalent amount of gasoline (NAS, 2004). This cost premium can be offset by efficiency improvements in the fuel cell vehicle. Currently, this technology is considered to be too expensive for the common consumer, but there is the potential for the development of fleets, which could be economical. It is expected that by 2020, the cost of hydrogen will drop below $2.00 per gallon of gasoline equivalent. This assumes that the field efficiency of fuel cells matches the theoretical calculated efficiency (NAS, 2004).

Current estimates of the cost of hydrogen from other sources vary widely and are highly dependent on the production methods used. Costs can be divided into production, transportation, and distribution components. Currently, the transportation of hydrogen via trucks costs from $4.00 to $9.00 per gge (gallon-gasoline equivalent), but this price is considered to be significantly higher than it would be if hydrogen were shipped through pipelines (U.S. Department of Energy, 2005).

The Case for Hydrogen

The expected economic, social, and environmental advantages of the hydrogen economy are well defined, although some benefits are disputed (e.g., Hammerschlag & Mazza, 2005; Rifkin, 2002; Romm, 2004). It is certain that hydrogen is widely considered a clean and abundant energy carrier when consumed with minimal leakage and waste.

Hydrogen as a Zero-Emissions Fuel

At the point of use, hydrogen can be considered a zero-emissions fuel when it is run through a fuel cell. A catalyst breaks down the hydrogen and then an electrochemical process occurs whereby hydrogen is combined with oxygen, usually from the ambient air, and the products are electricity and water vapor. When it is used, the only emission from a hydrogen fuel cell is water vapor, which may either be condensed and collected or released into the atmosphere where it will eventually return to the earth as rain or condensation. From an end-use standpoint, hydrogen is a zero-emissions fuel. This classification becomes less definite, however, when the full energy supply chain is examined. Emissions resulting from the hydrogen supply chain are examined in a later section.

Hydrogen as a Versatile Energy Carrier

There are two purposes for using energy carriers rather than an energy source. They are (a) to turn a less versatile energy source, such as coal or biomass, into a more useable form and (b) to store energy from a primary energy source, such as solar or wind energy, for use at a later time. Many of the feedstocks of hydrogen are currently used to provide energy today, in one form or another, but they are restricted in the roles they might play within the energy economy due to, for example, their inability to be directly substituted for liquid fuels.

Coal is one of the most abundant fossil resources in the world and it is domestically available in large stores in the United States. In addition, it is relatively inexpensive to combust compared with other energy sources. At one point, coal was used for transportation and home heating, but today, its use in the United States is nearly completely restricted to electrical generation. The energy services of transportation and home heating have been assigned to oil and natural gas, which often need to be imported, causing economic outflows and raising energy security concerns.

Hydrogen extracted from coal could supply energy services for current transportation and home heating needs and would do so with no end-use pollution. Moreover, hydrogen could be derived in large amounts sufficient to meet these demands. In this respect, hydrogen offers the potential to carry energy from coal in a more usable and convenient form. In this manner, many of our energy needs that today rely on imported fuels could instead rely on domestically available coal.

Similar arguments can be made for hydrogen produced by extraction from natural gas, biomass, or electrolysis of water using solar or wind energy sources. In all of these cases, an energy source that is currently technologically confined might play an expanded role in our energy economy. At the same time, a stream of environmental and security benefits would be created when energy value is carried by hydrogen.

Hydrogen for Energy Storage

Hydrogen is an excellent energy carrier for storage purposes, especially when compared with electrochemical means (e.g., batteries). Hydrogen has two features that make it well suited for energy storage. The first of these is the low level of energy degradation that occurs during the period of storage. Energy storage mediums such as deep-cycle batteries tend to leak energy over extended periods of time. If energy must be stored for a period longer than a few days, portions of the stored energy may be lost due to leakage within the battery. Hydrogen, however, can store energy with near-zero leakage for months at a time.

Another benefit is that additional storage capacity is relatively cheap. If energy is being stored in deep-cycle batteries, then the cost of the system will be highly correlated to the capacity of the battery bank. If capacity needs double, the cost of the system will nearly double, as will the storage volume and weight. With a hydrogen energy storage system, however, storage capacity and the electrical generating unit (the fuel cell) are separate pieces of hardware and the bulk of the price of the system is the fuel cell, whereas storage capacity is relatively cheap. Using hydrogen, if storage capacity of the system needs to be doubled, the price of the system may increase by only a fraction of the total price (NAS, 2004).

The Case Against Hydrogen

Hydrogen has a number of disadvantages that may counteract its promised benefits. Negative features include emissions before the point of use in the hydrogen supply chain; inefficiency compared with other carriers of electrical energy; the difficulty in developing a suitable storage medium for hydrogen to be used in highly mobile uses (such as cars); the challenge of coordinated infrastructure development required and its associated costs; the current high costs of the primary technology component, the fuel cell; and the high levels of investment that would be required to solve many of the technological problems associated with the use of hydrogen and to develop economies of scale necessary to lower critical component prices for a hydrogen economy.

Well-to-Wheels Emissions

Hydrogen's reputation as an emission-free energy system is one of the primary reasons for its promotion. When posited as a solar-hydrogen economy pathway, the system offers a strategy for providing essential energy services without the high environmental and social costs of fossil fuels or uranium. Considerable research literature attests to the costs of the latter (ranging from oil spills and nuclear accidents to mineral mining, acid rain, toxic pollution on catastrophic scales, and climate change). However, the environmental benefits of a hydrogen economy hinge on factors that are often neglected when point-of-use is the basis for evaluation.

If hydrogen is to be used in a power plant, combustion engine, or a fuel cell, the only byproduct is water. But this does not necessarily mean that hydrogen was produced in a nonpolluting manner. The environmental benefits of hydrogen are determined at the very beginning of the hydrogen fuel cycle, during the production of hydrogen gas (Consonni & Vigano, 2005). Despite being the most common element in the universe, hydrogen is not commonly found as a molecular hydrogen gas (H_2) on our planet. Instead, it is found as an element associated with a wide variety of other molecules and is commonly extracted from organic substances, fossil fuels, or water. All of these substances have molecular structures rich with hydrogen (Ogden, 1999).

Environmental problems associated with extracting hydrogen arise from the presence of other elements within the source molecule. When water provides the source of hydrogen, few environmental problems result, as the only other element in water is oxygen. When hydrogen is combusted or run through a fuel cell, it recombines with ambient oxygen in the atmosphere to produce water vapor. This means that a nontoxic gas is released into the atmosphere but reclaimed when the hydrogen is used, so that the chemistry of the atmosphere goes through no net change during the fuel cycle.

Environmental concerns arise when a source of hydrogen other than water is used. All biologically based sources (ethanol, methanol, and biomass) and fossil fuel sources (oil, coal, and natural gas) contain a number of other molecules that are released when hydrogen is extracted. Usually, these elements form the exact same pollutants, especially carbon dioxide, which hydrogen production was supposed to reduce. For example, steam reformation of natural gas produces a unit of carbon dioxide for every four units of hydrogen produced, along with carbon monoxide and water vapor. But this equals the amount of carbon dioxide that would be produced if natural gas were combusted as a fuel. This argument holds true for any carbon-based sources of hydrogen. As noted above, some fossil fuel sources of hydrogen (e.g., natural gas) would produce less carbon dioxide than current transportation technologies fueled by gasoline, but this comparative advantage may not be sufficient if, for example, reductions on the order of 60% to 80% are needed to address climate change threats (Byrne, Hughes, Toly, & Wang, 2006; Byrne, Wang, Lee, & Kim, 1998). Therefore, hydrogen's environmental profile depends on its source and the goals to be met.

Another important difference concerns the manner in which pollution is generated and ultimately dispersed. Hydrogen production from carbon-based fuels could occur at a centralized location. Hydrogen production in this manner may allow for sequestration of carbon and other pollutants, so that they are not released into the atmosphere (Rand & Dell, 2005). Large-scale carbon sequestration technology is still in a research phase, however.

The pollution problem needs to be examined thoroughly before plans for a hydrogen economy move further forward. If some effort is not made to devise a reasonable control system or to mitigate possible negative environmental effects, it is possible that the new hydrogen system could prove incapable of meeting sustainability criteria and thereby fail to separate itself from the core failing of the present energy systems. In brief, a hydrogen economy could garner major environmental benefits, or it could do little more than slow the pace of unsustainability of our current system.

Inefficiency of the Hydrogen-Fuel-Cell Energy Chain

Efficiency remains a significant challenge to the development of a hydrogen economy. Hydrogen-fuel-cell systems achieve relatively low cumulative efficiencies compared with other energy carriers and lead some to champion alternatives (Hammerschlag & Mazza, 2005).

Low cumulative efficiency results from the fact that hydrogen is simply an energy carrier rather than an energy source. Hydrogen energy systems differ from those requiring the user to put in some level of energy in order to extract many times that amount of energy, as with coal and oil. With hydrogen, its production takes more energy, either in the form of feedstock fuels or electricity, than is retrieved in the form of usable hydrogen at the end of the production process (Dell & Rand, 2001).

Losses occur along each step of the hydrogen fuel cycle. From its production and storage to distribution and then utilization in a fuel cell, energy is lost, resulting in cumulative decreases in efficiency (Rand & Dell, 2005). When two efficiencies are placed in a line of processes, total efficiency is calculated by multiplying the two together. Accordingly, as hydrogen passes through its numerous stages of production, energy losses accumulate even though each stage tends to have a relatively high efficiency rate compared with that of an internal combustion engine and other energy technologies. For example, when combining efficiencies of the five steps of hydrogen production, even if each step were 90% efficient, the overall efficiency falls to less than 60%. In reality, the efficiencies of the various stages of hydrogen development are likely to be much less than 90% (NAS, 2004). In addition to cumulative efficiency losses, other losses associated with the production of hydrogen's initial energy source, such as electricity and natural gas, contribute to the problem.

The user of a hydrogen energy system realistically is unlikely to receive more than 60% or so of the energy invested in the system and currently will probably not receive more than 20%. The reason that the hydrogen cycle will never achieve efficiencies reaching more than 60% has to do with thermodynamic limitations (Rand & Dell, 2005). More specifically, processes have theoretical efficiencies representing the highest input-output ratio that the process could ever achieve due only to physical limits. Actual efficiencies of such processes never reach theoretical limits because forces of friction and resistance cannot be completely eliminated. Such relationships mean that users of hydrogen will always receive less energy from fuel cells than was put into producing and transporting hydrogen to the user. Accordingly, many researchers believe that, rather than focusing on the development of hydrogen systems, policy should emphasize using initial power sources more efficiently. Such a goal could be accomplished by finding ways to use electricity directly, without converting it to another form. Failing that, systems promoting energy storage might use fewer steps, so as not to fall victim to the problem of cumulative efficiency losses. One option commonly encouraged in this vein is high efficiency, deep-cycle batteries for mobile options or large, efficient electrical storage systems for household and industrial electric production (Hammerschlag & Mazza, 2005).

Another response to the problem of hydrogen's efficiency difficulties involves restricting applications to those that enjoy clear advantages over rival energy sources and technologies. For example, hydrogen is particularly good for storing large amounts of energy over long time periods and for transferring and storing energy quickly (Rand & Dell, 2005; Suppes, 2005). In this regard, hydrogen applications may be limited to certain uses in the transport sector and for seasonal needs to resolve intermittency problems in a renewables-based electricity sector. In practice, certain tasks may also be served by a combination of a number of technologies with hydrogen energy systems, such as hydrogen-battery vehicles.

The Challenge of Hydrogen Storage and Distribution for Mobile Applications

Hydrogen storage for mobile applications can be a major obstacle in the transition to the hydrogen economy. Pressurized and liquefied molecular hydrogen storage could be used initially, but each has shortcomings. Accordingly, research and development efforts are now being directed toward advanced hydrogen storage technologies. Solid-state storage and nanotechnology could potentially prove to be valid options, especially as storage volumes increase, but these approaches are still highly experimental (NAS, 2004).

A primary concern for the storage of hydrogen is an energy density that would be suitable for long distance transportation applications. Currently, storage options for hydrogen either have too low an energy density to provide adequate range for a vehicle or the method of storage is too heavy, thereby reducing the efficiency of the vehicle. There are additional concerns with regard to the handling and distribution of hydrogen. In its pure form at room temperature, hydrogen is a diffuse gas that could prove difficult to handle and distribute without high losses. Although pure molecular hydrogen can be liquefied, the process involves high levels of energy loss. Moreover, hydrogen must be stored at such low temperatures to become a liquid that it could pose a health hazard to those handling it.

Research is under way to examine a number of novel methods for hydrogen storage that rely on the absorption of the gas within a solid or a liquid. Once absorbed by a substance, hydrogen would be stably contained until released through heat or pressure change. However, concerns revolve around the weight of the absorbing material, the cost of the absorbing material, and how to handle, dispose of, or reuse the material once it has released all of its hydrogen (NAS, 2004). All of these efforts are currently in the research and development stage and not ready for market integration.

The Difficulty of Coordinated Infrastructure Development

Traditionally, the automobile and transport fuel industries have operated largely independently, a condition that complicates economic development of the hydrogen transport economy. Expressed simply, the dilemma centers on what should come first, the hydrogen fueling stations or the hydrogen cars. The infrastructure required for energy generation, storage, and distribution in a country as large as the United States is projected to be in the many billions of dollars (Ogden, 1999). Energy infrastructure investments generally represent at least a 30-year commitment to a fixed energy system that cannot be easily modified later to meet changed market circumstances. Thus, initial investment decisions figure critically in the viability of an energy project.

Given this circumstance, investors in hydrogen supply markets may be unwilling to bear the risks of capitalizing an H_2 economy until evidence exists of a significant and growing market of hydrogen-fueled cars. Conversely, automakers may not be willing to build hydrogen-propelled autos unless hydrogen-fueling stations exist to serve them. It is quite difficult, as a consequence, to build a robust commercial sales platform establishing economies of scale for hydrogen technology.

U.S. experience with alternative fuel vehicle (AFV) programs is a testament to the difficulty (see Winebrake, 2000, 2002; Winebrake & Creswick, 2003). Innovating road vehicle technology when the fuel and manufacturing industries serving this market operate and invest with relative autonomy has proved far more difficult than federal and state program managers expected. The building of infrastructure for a hydrogen transport energy economy would likely face similar problems encountered with AFV development.

High Expense of Fuel Cells

In addition to the difficulty of coordinating infrastructure development, the individual components themselves can be expensive compared with conventional counterparts. This is particularly true of fuel cells used to convert hydrogen to electricity (Ogden, 1999). Currently, fuel cell prices are prohibitive, causing any device using one to cost several hundred times more than if a conventional power source is used. This is seen most evidently in the transport sector, where a fuel cell vehicle currently costs approximately $1,000,000 (National Public Radio, 2005).

In addition to the high cost of the fuel cell, use of many of the most desirable sources of hydrogen (e.g., renewable energy sources) would result in more expensive fuels than conventional sources now in use. Hydrogen from sustainable sources such as solar,

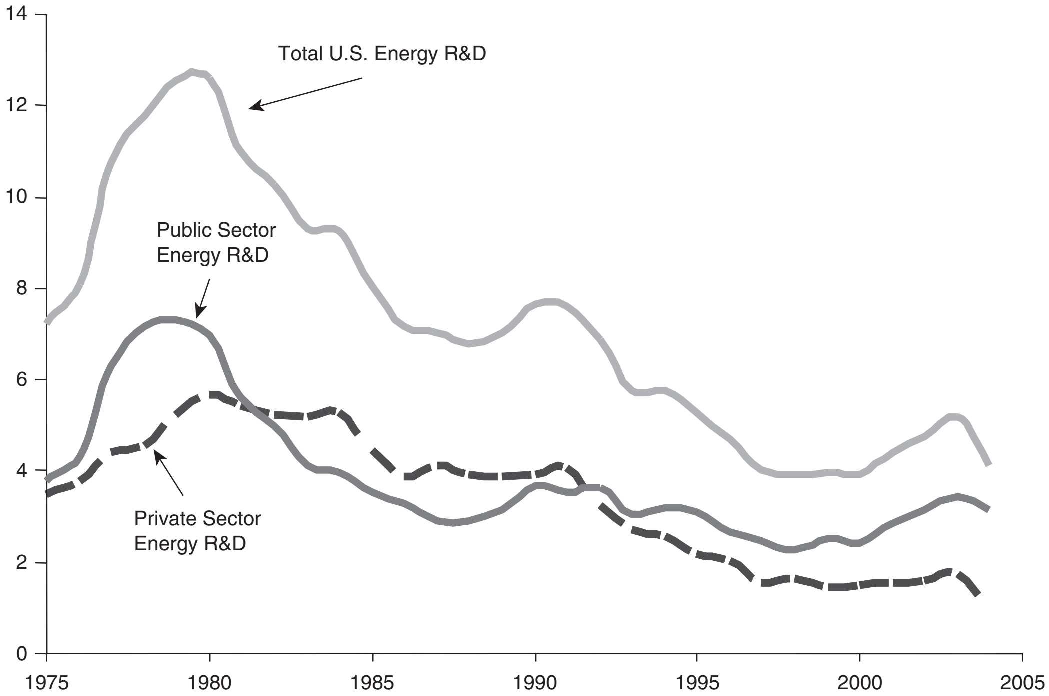

Figure 1. U.S. Research and Development (R&D) Investment in the Energy Sector in Billion U.S. Dollars
Source: Kammen and Nemet (2005), Peabody and Dooley (2004), and Dooley (2001).

biomass, or wind are more expensive than an amount of gasoline with the same energy content. Only hydrogen from natural gas and coal are currently cost competitive with gasoline. It is unfortunate that both have shown significant price volatility in recent years (Energy Information Administration, 2005).

The combination of high-cost desirable energy sources and technologies to enable H_2 use is likely to hamper the emergence of a hydrogen energy economy in the near- to midterm.

The Problem of Large-Scale Sustained Investment

To lower the costs of components, to create the level of infrastructure needed, and to solve technical problems still surrounding the effective use of hydrogen as an energy carrier, substantial investments will be needed from both government and industry sources. This investment will need to underwrite decades of research and development to solve technical problems and to develop less expensive components in the hydrogen-fuel-cell cycle.

In this vein, significant concern exists with regard to downward trends in both public and private sector energy research and development (R&D) investments in the United States (see Figure 1). This pattern casts doubt over the likelihood that national capital commitments will be sustained for the length of time needed to fully develop the hydrogen energy economy. Declining investments in new energy technology have recently been offset by rising support for fuel cell technology (see Figure 2). Government investments have been robust and are rising in specific states but have not yet attracted equivalently large private sector commitments. As a result, it is uncertain if a high level of decades-long support will be maintained to develop hydrogen-fuel-cell systems into commercially viable, widely used technologies.

Three Pathways to a Hydrogen Energy Economy

In considering the transition to a hydrogen energy economy, a number of alternative pathways can be identified, each with distinctive characteristics. Taking the hydrogen energy economy to refer to that portion of our energy system reliant on hydrogen as an energy carrier, the term includes infrastructure, labor, and materials necessary for hydrogen production, storage, transportation, and use. Two defining characteristics of the hydrogen energy economy therefore deserve

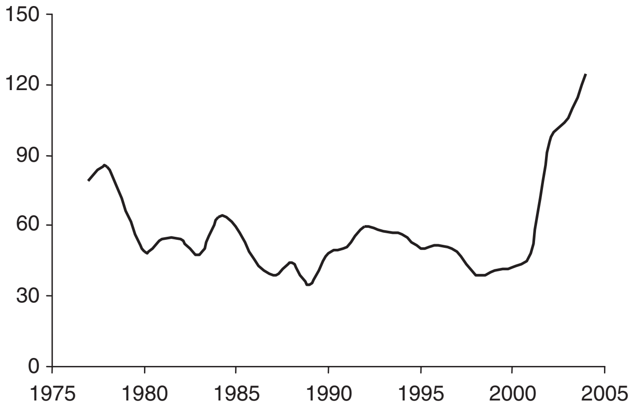

Figure 2. U.S. Public Sector Research and Development (R&D) Investment in Fuel Cell Technology in Million U.S. Dollars
Source: Kammen and Nemet (2005).

specification: applications of hydrogen as an energy carrier, and the sources of hydrogen.

By viewing the hydrogen energy economy in this manner, three pathways can broadly be portrayed: the niche hydrogen scenario, the transitional hydrogen scenario, and the sustainable hydrogen pathway. Economic, social, and environmental implications differ significantly for each pathway.

The Niche Hydrogen Scenario

In this scenario, hydrogen would exist as a fuel used for selected purposes, such as fleet vehicles, but it would account for only a small portion of national energy usage. As a result, hydrogen would fail to achieve widespread acceptance or accessibility as a fuel and would likely be found only in a few regions. As a transport fuel, hydrogen could be plagued by regional fragmentation, which would inhibit wider consumer acceptance. As well, significant variation in codes, standards, infrastructure, and equipment between regions could leave the hydrogen highway with many potholes.

Industrial and fleet use of hydrogen could stimulate additional applications, but infrastructure constraints would discourage large-scale uses. The niche hydrogen economy would be defined by a lack of uniformity among technology and a struggle between the supply of and demand for hydrogen. A “chicken and egg” scenario similar to the U.S. experience with AFVs would preoccupy development. Few incentives would exist to increase or create a hydrogen supply because niche applications would dominate.

Because of the limited use of hydrogen, the niche economy could not significantly achieve the desired benefits of using hydrogen as an energy carrier. Hydrogen would not be used in sufficient quantities to affect the environmental impact of energy use or to reduce reliance on foreign sources of energy. Net economic benefits from the use of hydrogen would remain questionable, as investments in infrastructure and technology may not earn adequate returns.

Many similarities exist between the niche pathway and the current state of U.S. hydrogen development. Specifically, hydrogen is beginning to find uses, but supply networks are localized around a few urban areas or within states heavily promoting these systems. Uses for hydrogen are primarily for corporate or governmental fleets and are almost entirely dependent on governmental incentives. If these decline or disappear, there are few who believe that a hydrogen economy could advance.

Transitional Hydrogen Scenario

Under this scenario, hydrogen could supply a significant portion of energy needs (more than 10%, for example, of transport and nontransport uses). The primary source for hydrogen would be fossil or biological fuels due to their comparatively low cost and the availability of existing infrastructure. Greater uniformity would appear between the storage and distribution of hydrogen among regions, and nationwide hydrogen networks would develop so that one could drive from state to state or across the country on hydrogen fuel (Dunn, 2002).

At its core, however, the national energy system would remain fossil-fuel-based under this scenario. Many proponents of hydrogen believe that the surest pathway to a hydrogen economy is to evolve the existing system without significant fuel modifications in the near term (i.e., the next 10 to 15 years; see Consonni & Vigano, 2005; NAS, 2004; Romm, 2004). The bulk of energy in this system would continue to come from carbon-heavy sources, effectively adding a stage or an option to the current energy economy, rather than steering toward a new one. Current environmental and resource problems associated with fossil fuels would remain, although some could be partially reduced by using a greater diversity of domestic fuels for a wider variety of purposes. Modest improvements in national energy security and lower carbon emissions growth might be expected, especially if hydrogen is mainly harvested from domestic natural gas.

The infrastructure needs for this pathway are mostly in place. At present, more than 90% of the hydrogen produced in the United States comes from steam reformation of natural gas. Therefore, continued reliance on natural gas and other fossil fuels as hydrogen sources can take advantage of existing supply and distribution infrastructure, albeit at significantly expanded capacities over time. Greater hydrogen production could be achieved by connecting additional reformation facilities to the existing natural gas production and distribution system, a relatively low-cost solution. Escalating demand for hydrogen should foster improvements in economies of scale and diffusion of H_2 uses, but it would eventually bring the need for major investments to upgrade infrastructure.

The plausibility of the transition scenario has its enthusiasts and skeptics (Dunn, 2002; Hammerschlag & Mazza, 2005; Rand & Dell, 2005; Romm, 2004). Regardless, the scenario's modesty in technological and economic innovation may enable it to progress in the face of inertial resistance to change. At the same time, this very factor may mean that progress on energy sustainability issues slows.

Sustainable Hydrogen Scenario

A hallmark of a sustainable hydrogen economy would be the source of hydrogen. In this alternative, renewable energy sources would be substantially used to produce hydrogen, accomplishing this task through electrolysis of water by using solar and wind power and possibly biological fuels in conjunction with carbon sequestration. The current energy system would need to be greatly modified or replaced by a new generation built on the logic, economics, and distinctive system architecture of renewable energy.

A sustainable H_2 scenario could first follow a transitional pathway, taking full advantage of remaining natural gas reserves before switching to renewables. But there are important reasons to consider the need for committing to renewable energy principles from the onset so that the differences between what Lovins (1979) long ago characterized as the incompatible system dynamics of "hard path" and "soft path" systems are addressed. Whereas Lovins and others contemporarily suggest that the differences may be manageable (see Hawken, Lovins, & Lovins, 2000), others caution that this conclusion could be wrong (e.g., Byrne & Toly, 2006).

Although financially the most expensive scenario and technologically the boldest departure from the energy status quo, a sustainable hydrogen pathway would likely also result in the greatest energy security and environmental gains. When its distributed energy architecture—dictated by the need to use diverse, locally available renewable energy sources with comparatively lower densities—is combined with the unique attribute of renewables—an economics that is almost entirely dependent on capital costs and technological innovation and virtually independent of fuel price—the sustainable hydrogen scenario promises the highest energy security possible. And it is the only hydrogen scenario that can offer the prospect of dramatically lower greenhouse gas emissions. The niche and transitional hydrogen scenarios would almost certainly affect only the rate of increase in carbon emissions. Even with sequestration of carbon, a transitional hydrogen economy probably cannot deliver significant emissions cuts because only a percentage of emissions (perhaps as high as 85%) can be biologically stored, and the energy requirements to power sequestration technology would surely involve expanded use of fossil fuels. Finally, because hydrogen is an energy carrier and not an energy source, large quantities of nonrenewable energy must be expended for a transitional scenario built on fossil fuels to work. Thus, greenhouse gas emissions cannot fall by the 60% or more needed to realize climate sustainability (Byrne & Toly, 2006; Byrne et al., 1998).

In sum, measured in terms of the energy status quo, a sustainable hydrogen energy economy may be expensive and require radical departure from the prevailing technological order. On the other hand, it may be the only strategy that can actually contribute to solving the fundamental problems of the existing energy regime. Whether this approach will have a role or whether it is better to focus on direct uses of renewable energy cannot be easily decided at this juncture.

Alternatives to Hydrogen-Fuel-Cell Systems

Not only will hydrogen have to be proven suitable and preferable to conventional energy technologies, it will also have to fend off a number of competitors that can offer similar services and benefits but at lower cost and possibly greater social and environmental benefits. This includes competitors in the near term in the sector where hydrogen could be considered strongest—transportation.

The alternative energy technologies considered below are not all of those that may present competition to hydrogen but are those options that present the most significant near-term competition. These technologies are batteries, hybrid electric vehicles, and the use of biofuels.

Batteries

Batteries as energy storage devices are common in the world today and used in a wide array of applications. Watches, flashlights, cell phones, cars, and many other technologies rely on batteries to operate conveniently. Because the efficiencies of battery systems can be greater than those for a hydrogen-fuel-cell chain, and some are much less expensive, some believe that research attention should focus on them rather than fuel cells (Rand & Dell, 2005). There are important exceptions when hydrogen could be preferable, as noted below.

Batteries are particularly limited in terms of transport applications by the amount of time it takes to recharge. Vehicles are often required to run for lengths of time and distances that could exceed the capacity of a vehicle's battery system without sufficient time to recharge. Buses that travel all day, trucks carrying goods great distances, ships, taxis, and other such vehicles that run for 8 or 9 hours a day could not logistically rely on batteries. For these situations, hydrogen might be used because, instead of several hours of recharge time, a hydrogen vehicle can refuel in a few minutes, comparable with the time spent at a gasoline pump for refueling (Suppes, 2005). On the other hand, when overnight recharging, for example, is acceptable, battery-assisted transportation may be more economical than fuel cell vehicles.

Hybrid Vehicles

A hybrid vehicle uses two or more energy resources to provide motive power—an internal combustion engine using gasoline (or other liquid or gaseous fuel) and an electric motor powered by energy stored in batteries (typically supplied by regenerative braking). The design can produce both environmental and economic benefits. The use of hybrid gasoline-electric vehicles is gaining popularity among consumers and is being integrated into government and corporate fleets in the United States. The primary benefit of these vehicles is increased fuel efficiency and significantly lower sulfur and carbon emissions. The performance, in terms of horsepower, is comparable for hybrid vehicles.

At present, hybrid vehicles are considered the most viable alternative propulsion system for transportation, and many researchers believe that these vehicles will play an important role in reducing oil demand and greenhouse gas emissions. It is also believed that hybrid vehicles may provide an attractive transition between conventional technology and hydrogen-fuel-cell technology.

Assorted technologies used in the hybridization of vehicles further differentiate these vehicles from conventional ones. Five different technologies are often used in the hybridization process: (a) idle-off capability, (b) regenerative braking, (c) downsized engines, (d) electric drive-only operation only upon acceleration, and (e) extended battery electric range. Together, these approaches enhance fuel economy by shifting a part of the vehicle's propulsion requirements to the electric motor and enabling a smaller engine to perform equivalent tasks. Between 2006 and 2008, the hybrid car market in the United States will include 20 models, ranging from compacts and sedans to minivans and SUVs. In 2000, 9,350 hybrids were sold in the United States. By October 2005, the number had increased to more than 170,000, an 18-fold increase (Union of Concerned Scientists, 2005).

Over the past several years, manufacturers have observed a significant increase in interest for heavy duty hybrid vehicles. Most orders are for transit buses; however, hybrid electric trucks have also been developed for delivery and utility applications. A recent inventory documents an increase of 34% in active bus services and 65% in hybrid bus orders (American Public Transportation Association, 2004).

Hybrid vehicles have proved successful at boosting fuel economy, with the Union of Concerned Scientists (2005) indicating that, on average, hybrid vehicles have 65% to 101% better fuel economy than today's gasoline vehicles. Emission advantages of hybrids have also been observed: Engines are heated very quickly because hybrids rely on smaller and lighter engines, which reduces start-up emissions. In motion, hybrids use electric motors to further cut pollution. Over a lifetime of 15 years, hybrid vehicles reduce CO_2 equivalent emissions by 31 to 40 tons, compared with conventional counterparts (Friedman, 2003). With lower capital costs and valuable improvements in energy security and environmental sustainability, hybrids offer important competition to fuel cell vehicles.

Biofuels

The term *biofuels* refers to a group of energy sources derived from living organic substances. Included in this category are biodiesel, ethanol, methanol, biogas, producer gas, and others. In the United States, interest in biodiesel is growing due to several attractive properties: significant reductions in carbon dioxide emissions, an ability to be used in conventional diesel engines, and costs that are comparable with petrodiesel. Biodiesel is usually blended with petroleum diesel in 5% to 20% proportions or sold in a pure 100% form. It can be produced from a variety of feedstocks and any number of chemical reactions, but transesterification of soybean or rapeseed oils is currently the most economically attractive process. A high conversion of 98% of the feedstock to biodiesel is usually achieved and a considerable quantity of glycerine (a profitable byproduct) is produced (www.biodiesel.org).

Biodiesel has extremely low sulfur content (0 to 24 parts per million) and a higher lubricity than petroleum diesel, but the energy content is approximately 11% less (thereby reducing fuel economy). Burning biodiesel (B100) creates 78% less carbon dioxide, 56% less hydrocarbons, 43% less carbon monoxide, and 56% less particulate matter. However, there is a slight increase in nitrogen oxides emitted (6%) when biodiesel is burned in lieu of petroleum diesel.

The market for biodiesel has grown steadily in the past few years. Only 500,000 gallons were produced in the United States in 1999, but more than 125 million gallons were sold in 2005. Beginning in 2007, the Environmental Protection Agency will implement stricter emission standards for particulate matter and nitrogen oxide released by diesel combustion. Blending petroleum diesel with biodiesel is a simple, economic method to drastically reduce the emissions of these two air pollutants. As a consequence, demand for biodiesel is expected to continue growing at a rapid pace.

Its comparatively low cost, ready use without new infrastructure needs, and important contribution to transport emission reductions make it another important competitor to hydrogen. It is certain that its expanding use will complicate market entry for hydrogen.

Whither the Hydrogen Highway?

Although hydrogen can offer several benefits, numerous drawbacks as well as the presence of several competitors indicate that building a hydrogen energy economy will be no easy task. Moreover, outstanding technological and economic hurdles will prevent hydrogen from being ready for substantial use in the near and possibly intermediate future. As a result, an H_2 strategy will need to enlist political and economic support that will be consistent and evolving over several decades. These are not qualities normally found in the real world of politics and business competition. This observation prompts a question: Are there appropriate uses of hydrogen deserving concerted efforts against long odds? Perhaps this question can only be answered affirmatively for H_2 options that facilitate progress toward a sustainable energy future.

Even if hydrogen is harvested from renewable sources, thereby meeting an important indicator of sustainability, it may still be preferable to rely on direct use of renewables or battery storage. This points to hydrogen's strategic value. It is unlikely to be the anchor of change; rather, it appears to be best suited as a companion to renewable energy with the latter assuming the role as the driver of energy change. Thought of in this way, hydrogen could be important as society shifts to a solar economy. Due to their intermittency, these energy sources require energy carriers and storage to supply energy when they are not available. Currently, hydrogen is one of the only carriers that could accomplish this task on the scale that would be needed to convert a significant portion of our energy economy to intermittent renewable resources. Two alternative methods of dealing with intermittency would be preferable but could ultimately be unable to solve the complete intermittency problem. The first option would be to minimize the amount of energy that would need to be carried by using a diverse portfolio of renewable energy sources. When one is not available, others may be. This would be preferable when it is possible because it avoids the energy losses associated with any method of storing energy. The second option would be the utilization of pumped hydro energy storage. This is an efficient and inexpensive method of energy storage, but it is limited in scale by the relatively few sites that have suitable terrain. When these two options are not sufficient, which will often be the case, the shift to a solar economy will need to rely on hydrogen as an energy carrier and method of storage. This understanding of hydrogen's future may be the most compatible with society's search for a sustainable energy future.

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