A HYDROGEN FUTURE?

An Economic and Environmental Assessment of Hydrogen Production Pathways

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NATURAL RESOURCES DEFENSE COUNCIL
ISSUE PAPER: NOVEMBER 2005

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ACKNOWLEDGMENTS

Tim Lipman provided the technical analysis upon which this report is based. Tim Lipman, Dan Lashof, Roland Hwang, Geoff Fettus, Tom Cochran, Chris Paine, and Nathanael Greene all provided invaluable assistance in the writing and editing of this paper.

EXECUTIVE SUMMARY

In recent years, political leaders, the media, and even some auto manufacturers have embraced hydrogen as the nation's best hope for addressing the rapidly accelerating threats posed by global warming and U.S. dependence on imported oil. Current enthusiasm for hydrogen is largely predicated on its potential advantages over petroleum as a future vehicle fuel. Proponents point out that hydrogen fuel produces far less air and global warming pollution than conventional fuels, and that it can be produced in America—holding out the promise of energy independence. Less widely appreciated or discussed, however, is how hydrogen's costs and environmental benefits depend on where it comes from.

Hydrogen cannot be found and extracted from the earth's crust. Rather, hydrogen must be made—and how it is made matters. This report identifies current and proposed future sources of hydrogen, and examines the costs and environmental impacts of different methods of producing and using hydrogen as a means of assessing its desirability as a substitute for conventional fuels.[1]

Our assessment shows that the least expensive and most developed methods of hydrogen production in use today are not necessarily environmentally sustainable. For example, one of the cheaper options currently available, producing hydrogen from coal without carbon capture and storage, will further aggravate the problem of global warming. The most sustainable ways to produce hydrogen in the future are from wind, solar, and biomass resources, and, under certain circumstances, from fossil-fuel sources with carbon capture and storage. However, there are significant hurdles that stand in the way of commercializing clean and sustainable means of producing hydrogen, as well as developing the vehicle technologies required to efficiently store and use hydrogen, and building the extensive infrastructure that would be needed to support its widespread use in motor vehicles. As a result, it will take at least two decades before hydrogen can even begin to make a significant contribution to reducing global warming pollution, improving air quality, and reducing U.S. oil dependence.

This study reinforces conclusions reached by a number of independent experts and by the National Academy of Sciences (NAS),[2] foremost that hydrogen will not provide an immediate solution to America's energy and climate crises. It could be a potential long-term solution to improving energy security and reducing global warming risks, if—and only if—it is largely produced from renewable resources, or perhaps from non-renewable technologies that include carbon capture and storage.

Any realistic assessment of the hydrogen option suggests that the transition to a hydrogen economy is far from inevitable. In fact, a focus on hydrogen must not detract from other strategies and technologies that could produce much larger environmental and energy security benefits in the near term. For example, the cumulative oil savings that could be achieved by 2020 through off-the-shelf efficiency improvements to conventional vehicles are 25 times greater than the oil savings achievable over the same time frame through an aggressive deployment of hydrogen fuel cell vehicles.[3] Even by 2030, achievable oil savings from conventional and hybrid vehicle fuel economy improvements are still five times as great as those from fuel cell vehicles.[4] Meanwhile, other vehicle and fuel options, such as hybrid vehicles that run on ethanol made from agricultural waste or energy crops, or rechargeable electric vehicles, appear to have at least as much potential as hydrogen to substantially reduce oil consumption and vehicle-related global warming pollution in the coming decades.

America cannot wait to curb global warming pollution or cut oil dependence until the hydrogen economy is ready. A responsible, economically sensible energy policy requires a comprehensive approach that emphasizes both near-term results and investment in long-term solutions. Specifically, the United States should act now to implement the following policies:

- Adopt near-term performance standards that require automakers to cut the oil consumption and global warming pollution of their fleets by deploying technologies that reduce carbon emissions, save fuel, or do both.[5]

- Accelerate deployment of off-the-shelf and near-term vehicle technologies and fuels, such as hybrid electric vehicles and biofuels like cellulosic ethanol, which can reduce oil dependence and global warming pollution while providing a potential transition to hydrogen fuel cells.

- Promote the strategic deployment of fuel cells over the next decade, including conducting fleet testing of fuel cell vehicles in the nation's smoggiest cities to acquire real-world experience with commercialization challenges while also achieving immediate air quality benefits.

- Support continued research and development into fuel cell vehicle technology and advanced hydrogen system technologies, complemented with research, development, and deployment efforts targeted at producing hydrogen from wind, solar, and biomass resources and from fossil-fuel sources with carbon capture and storage. These are the most sustainable options for potential future hydrogen production.

- Support long-term research and development efforts to continue exploring clean-energy alternatives to hydrogen such as biofuels, plug-in hybrids, and battery electric vehicles.

BACKGROUND ON HYDROGEN AND FUEL CELLS

Hydrogen is the most abundant element in the known universe. The hydrogen molecule (H_2) is a colorless gas at room temperature and, being light relative to other gases, will disperse rapidly up through the atmosphere unless it is contained. Worldwide, some 50 million metric tons of industrial hydrogen (about 9 million metric tons in the United States) are produced for use in oil refineries and in the manufacture of fertilizers and chemicals. Hydrogen is also formed through various natural processes, but it tends to accumulate only deep underground where it occurs as the result of bacteria acting on ancient vegetable and animal remains. Recent research suggests that underground stores of hydrogen may be much larger than previously thought, but the economic and environmental hurdles to accessing these natural reservoirs are likely to be prohibitive.[6]

Hydrogen has been considered as a fuel for many years, but over the past 10 to 15 years advances in fuel cell technology have spurred an enormous wave of interest in its potential energy applications, particularly for the transportation sector which—despite long-standing concerns about U.S. dependence on imported oil—remains nearly exclusively dependent on petroleum fuels. Fuel cells, which can theoretically be made in a wide range of sizes for any number of potential applications, have the ability to efficiently convert hydrogen to electricity using special membrane materials and an electrochemical rather than combustion process. Over the past decade or so, billions of dollars in private and public sector research and development funding have flowed to hydrogen technologies. Hydrogen fuel cell vehicles have also emerged as the centerpiece of the Bush administration's strategy for addressing petroleum-related energy security and climate concerns. In 2003, the administration announced plans to spend $1.7 billion over five years on hydrogen fuel cell vehicles and supporting fuel infrastructure as part of its FreedomCAR and Fuel Partnership program.

Investments to date in hydrogen and hydrogen fuel cells have spurred significant technological improvements, but have also revealed the many difficulties of designing fuel cell and hydrogen storage and dispensing systems that are practical, cost-effective, and safe to operate. In this context, it is worth noting that hydrogen can also be used apart from fuel cells as a fuel for combustion engines and gas turbines in a variety of transport as well as stationary applications (potential examples include hydrogen internal combustion engine vehicles and hybrid electric vehicles; hydrogen engines and/or turbines for heavy-duty transportation applications such as forklifts or maritime vessels; and hydrogen gas turbines for power generation). These uses may eventually help support the development of a hydrogen distribution infrastructure even in market segments where fuel cells have not yet become established. At best, however, they are likely to represent only an interim step in the gradual deployment of hydrogen-based technology. Ultimately, in the transportation sector only fuel cells—which can take advantage of hydrogen's unique characteristics to achieve substantially higher efficiencies than combustion-based technologies—are likely to make hydrogen competitive and to provide the overall benefits that would compensate for its higher costs (per unit of energy content) relative to conventional fuel alternatives. The successful development and commercialization of fuel cell technology is therefore another key prerequisite for establishing the long-term viability of hydrogen as a primary fuel for the U.S. transportation sector.

SOURCES AND METHODS FOR PRODUCING HYDROGEN

In theory, hydrogen can be derived from any hydrocarbon fuel, including oil, coal, or natural gas as well as biomass and organic waste, all of which are largely composed of hydrogen and carbon atoms in various combinations. Hydrogen can also be produced by splitting water into its constituent elements using a process known as electrolysis, which requires electricity. Costs as well as air emissions, land use, and other environmental impacts of hydrogen production depend on how hydrogen is made and what it is made from.

Steam reformation of methane using natural gas as the feedstock is the dominant technology used to produce industrial hydrogen worldwide, and is the leading pathway under consideration for a substantial near-term expansion of hydrogen production in the United States. Longer-term scenarios for a fully sustainable hydrogen economy with low or zero net global warming emissions generally assume that hydrogen will be produced using electricity generated by renewable resources (such as wind or solar power), from coal or other hydrocarbons using processes that allow for the capture and storage of associated carbon dioxide emissions, or from biomass using a variety of potentially promising thermochemical or biochemical conversion processes. Other options for producing hydrogen exist but are not as well developed. These include thermal conversion of water using heat from nuclear or solar thermal (as opposed to photovoltaic) power stations, hydrogen-producing algae, and production using waste gases from landfills or water treatment plants.

Steam methane reforming using natural gas

This is the dominant technology used to produce large amounts of industrial hydrogen worldwide, mostly for applications in oil refineries and in chemical or fertilizer production. It is the leading pathway under consideration for a substantial near-term expansion of hydrogen production in the United States. In general, steam reformation can be used with any light hydrocarbon such as methane, butane, propane, etc. However, the use of natural gas as the feedstock for this process has several drawbacks. First, North American supplies of natural gas are likely to be increasingly constrained given projected demand growth (even without hydrogen production) and prices have recently risen dramatically. Increased imports of liquefied natural gas could alleviate domestic shortages, but would raise some of the same energy security concerns as imported oil. And additionally, because natural gas is a fossil fuel—albeit one with lower carbon content than oil or coal—this method of producing hydrogen contributes to global warming unless associated carbon emissions are captured and stored. Extracting and moving natural gas (via pipeline) may also harm ecologically sensitive areas.

Gasification of coal and other hydrocarbons

Though less mature than steam methane reforming, this method is also relatively well established, with more than 15 gasifier systems in place worldwide, mostly to produce hydrogen for ammonia fertilizer. Different systems exist but all use steam and air or oxygen to gasify coal and generate process heat. Costs are expected to be relatively low. Coal is an abundant fossil fuel resource globally and in the United States, which has some of the world's largest coal reserves. In contrast to steam reformation, gasification processes can also be used with a variety of heavier hydrocarbons, including heavy residual oils and other low-value refinery products, as well as coal. However, making hydrogen from coal or heavy oil would generate large amounts of carbon emissions. Unless these emissions are captured and stored, global warming concerns would preclude reliance on this production method. Furthermore, the upstream impacts of coal mining are associated with significant land and water quality concerns.

Electrolysis

The splitting of water molecules, or electrolysis, is the oldest known electrochemical process and has been used in the commercial production of hydrogen since the early 1900s. Research into more efficient electrolyzers is ongoing, but costs remain relatively high. In terms of energy security, however, electrolysis has the advantage of being able to utilize domestically-produced electricity. The United States has significant renewable resources and hydrogen production could offer a means of capturing and storing this potential in remote areas or during off-peak hours. Since oil is not widely used for power production, even the use of conventional grid electricity would likely provide some energy security benefits. The environmental impacts of electrolysis depend on the fuels and technologies used to generate the electricity used in the process. Use of conventional grid power would generate more global warming pollution than steam methane reforming with natural gas. Use of renewable power would allow for a truly low- or zero-emissions fuel cycle, but near-term benefits of renewable power may be greater if used to displace other sources of electricity rather than to create hydrogen.

Gasification of biomass

This technique can be used to produce hydrogen in a number of ways. These typically involve heat (thermochemical processes) or anaerobic digestion using fermentative bacteria (biochemical processes). Biomass-based hydrogen production could potentially make use of a variety of domestic feedstocks, including dedicated energy crops as well as crop and livestock wastes or residues. Such resources are abundant and widely distributed throughout the country. If these feedstocks are sustainably cultivated, this method of hydrogen production would result in low to no net greenhouse gas emissions. However, the large-scale production of dedicated feedstocks and the collection and transport of crops and residues may raise other air, land, and ecosystem concerns.

Nuclear power

Nuclear power can be used for electrolysis, or to supply heat to reduce the energy requirements associated with steam reformation of natural gas, or in a thermochemical process for dissociating water molecules. The uranium used to power nuclear plants is a relatively abundant domestic resource, but substantial hurdles exist to the expansion of nuclear power. These include high capital costs, issues of waste management and disposal, reactor safety, weapons proliferation, and lack of public acceptance. While the use of nuclear energy for hydrogen production is attractive from a carbon-limiting perspective, it raises other serious environmental and health concerns related to the mining and processing of uranium, the potential for accidents, and the management and disposal of radioactive waste.

Table 1 summarizes some of the likely advantages and disadvantages of the primary hydrogen feedstock and production pathways that have been identified to date.

Table 1. H2 Production Pathways, Advantages and Disadvantages

Method	Energy Security Considerations	Environmental Considerations
Steam Methane Reforming Using Natural Gas As Feedstock	**(+)** A mature technology, already used to produce large amounts of industrial hydrogen worldwide. **(-)** Constrained domestic supplies of natural gas and high prices	**(-)** Burning natural gas contributes to global warming. **(-)** Extracting and transporting natural gas could harm sensitive landscapes.
Gasification of Coal and other Hydrocarbons	**(+)** Relatively well-established and low cost process. **(+)** U.S. has some of world's largest coal reserves. **(+)** Process can be used with a variety of heavier hydrocarbons, including heavy residual oils and other low-value refinery products.	**(-)** Making H_2 from coal or heavy oil would generate large amounts of carbon emissons. **(-)** Coal mining can degrade land and water quality.
Electrolysis Using Conventional Grid or Renewable Power	**(+)** Multiple sources available. **(+)** Use of conventional grid electricity would provide some energy security benefits since oil is not widely used for power production. **(+)** Using renewably-produced electricity to produce H2 could offer a means of capturing and storing this energy in remote areas or during off-peak hours. **(-)** Costs remain relatively high.	**(+)** Use of renewable power would produce low to zero-emissions. **(-)** Use of conventional grid power would generate more global warming pollution than steam methane reforming with natural gas. **(-)** Near-term benefits of using renewable power may be greater if used to displace other sources of electricity.
Gasification of Biomass	**(+)** Feedstocks are abundant and widely distributed throughout the country.	**(+)** If feedstocks are sustainably cultivated, process has low to no net global warming emissions. **(-)** Large-scale production of feedstocks and collection and transport of crops and residues may raise air, land, and ecosystem concerns.
Nuclear Power	**(+)** Uranium to power nuclear plants is a relatively abundant domestic resource. **(-)** High capital costs and concerns about reactor safety and weapons proliferation.	**(-)** Issues of waste management and disposal and extraction and processing of uranium. **(+)** low global warming emissions.

COST AND INFRASTRUCTURE ISSUES

Cost is obviously an important factor, both in terms of the overall viability of a hydrogen-based economy and in assessing which production pathways and feedstocks show promise for making hydrogen competitive with conventional fuels. Another important related factor is the need for new infrastructure to support hydrogen production and distribution. Infrastructure needs vary for different hydrogen pathways depending on whether they lend themselves to centralized, large-scale production or smaller-scale, distributed production. The former generally implies larger distribution costs, which—in the near term, at least—would likely be accomplished by pipeline or by using trucks to haul hydrogen in liquid form, in high-pressure gas tubes, or in refillable trailers for dispensing compressed gas. Distribution costs tend to be less significant for decentralized hydrogen production at small-scale steam methane reforming or electrolysis facilities, or where hydrogen is a by-product of chemical plant operation. In these situations hydrogen can be used as it is produced or it can be compressed, stored, and dispensed for later use in stationary or automotive applications.[7] The discussion that follows generally focuses on delivered costs of hydrogen;

assumptions about distribution methods and costs are therefore embedded in the cost ranges cited for different hydrogen production pathways.[8]

In comparing these and subsequent cost estimates presented in this paper it is useful to note that 1 kilogram of hydrogen has roughly the same energy content as 1 gallon of gasoline. A one-to-one comparison of kilograms to gallons would be misleading, however, because hydrogen will most likely be used in fuel cells that are substantially more efficient than internal combustion engines. Thus, the per-mile cost of hydrogen at $3 per kilogram (kg) would be competitive with gasoline at $1.50 per gallon, if one assumes that the hydrogen is used in a fuel cell vehicle that is twice as efficient, on average, as a conventional vehicle. So, at average U.S. gasoline prices of $2.50 per gallon, hydrogen production costs $5 per kg are likely to be competitive.

Fossil fuel-based hydrogen production

At present, steam reformation of methane using natural gas and coal gasification offer the lowest-cost means of producing hydrogen. Costs for the former depend on natural gas prices, production scale, and other variables, but now range from $2 to $5 per kg of hydrogen delivered in gaseous form and stored at high pressure.[9] Delivered costs for hydrogen produced from large-scale coal gasification facilities are similar, ranging from $2.00 to $2.50 per kg. It has been estimated that future large-scale hydrogen production costs for both of these options will decline further—to as low as $1.50 per kg for coal gasification and $1.60 per kg for steam methane reforming at centralized facilities with pipeline delivery. Future costs for small-scale, decentralized steam methane production, meanwhile, could be as low as $2.00 to $2.50 per kg.

The cost figures cited above for future large-scale hydrogen production from coal or natural gas generally include estimated costs for carbon capture and storage, which would be necessary to make any fossil fuel-based method of producing hydrogen sustainable from a climate perspective. Carbon capture itself would likely be feasible only at large, centralized hydrogen production facilities. In terms of carbon storage, a variety of approaches are possible, including terrestrial, microbial, geologic and mineral. Terrestrial and microbial options include photosynthesis and other biological processes that increase carbon dioxide uptake from the atmosphere. Geologic storage solutions entail storing carbon in deep geologic formations (e.g., mined coal beds and salt domes, deep saline aquifers, or depleted oil and gas reservoirs). Mineral storage involves reactions to form carbonates or bicarbonates. Each of these storage options raises a variety of technical, environmental, and economic issues and none has yet been consistently demonstrated on a large scale. Thus, while the available literature typically estimates long-term costs for carbon capture and storage on the order of $10 per ton of carbon, uncertainty about this aspect of any fossil fuel-based hydrogen production pathway remains.

Renewably produced hydrogen

Renewable pathways for producing hydrogen avoid generating global warming pollution in the first place and, depending on the viability of carbon capture and storage, may therefore prove more attractive in the long run. At present, however, these options are generally more expensive. For example, current cost estimates for electrolysis using wind power range from $7 to $11 per kg of delivered hydrogen, while electrolysis using solar photovoltaic power is estimated to cost anywhere from $10 to $30 per kg. (By comparison, current costs for electrolysis using conventional grid power in the United States are estimated at $6 to $7 per kg of delivered hydrogen.) At $5 to $7 per delivered kg (assuming medium production scale and liquid transportation by tanker truck), current costs for producing hydrogen from biomass are also higher than for the more conventional steam methane reformation or coal gasification methods.

As with the fossil fuel-based hydrogen production pathways described previously, the costs for various renewable options can be expected to decline with further technology improvements. According to some estimates, future costs for electrolysis using wind or solar power may be as low as (or lower than) $3 per kg of delivered hydrogen. Meanwhile, costs as low as $1.50–$3.50 per kg are believed possible for future biomass-based hydrogen production systems, assuming larger production scales and pipeline delivery. One of the most promising biomass-based options may be pyrolysis, a thermochemical conversion process for which estimated future costs are as low as $1 per delivered kg. In some cases, favorable economics may be achieved by integrating the production of hydrogen with the production of electricity and other valuable co-products. For example, coupling electrolyzers with renewable electricity generators could provide a means of storing intermittent wind or solar power that becomes available during off-peak hours when it would otherwise have little value.[10] Similarly, several of the processes available to make hydrogen from biomass can yield other useful outputs such as adhesives, carbon black, activated carbon, polymers, fertilizers, ethanol, various acids, Fischer-Tropsch diesel fuel, waxes, and methanol.[11]

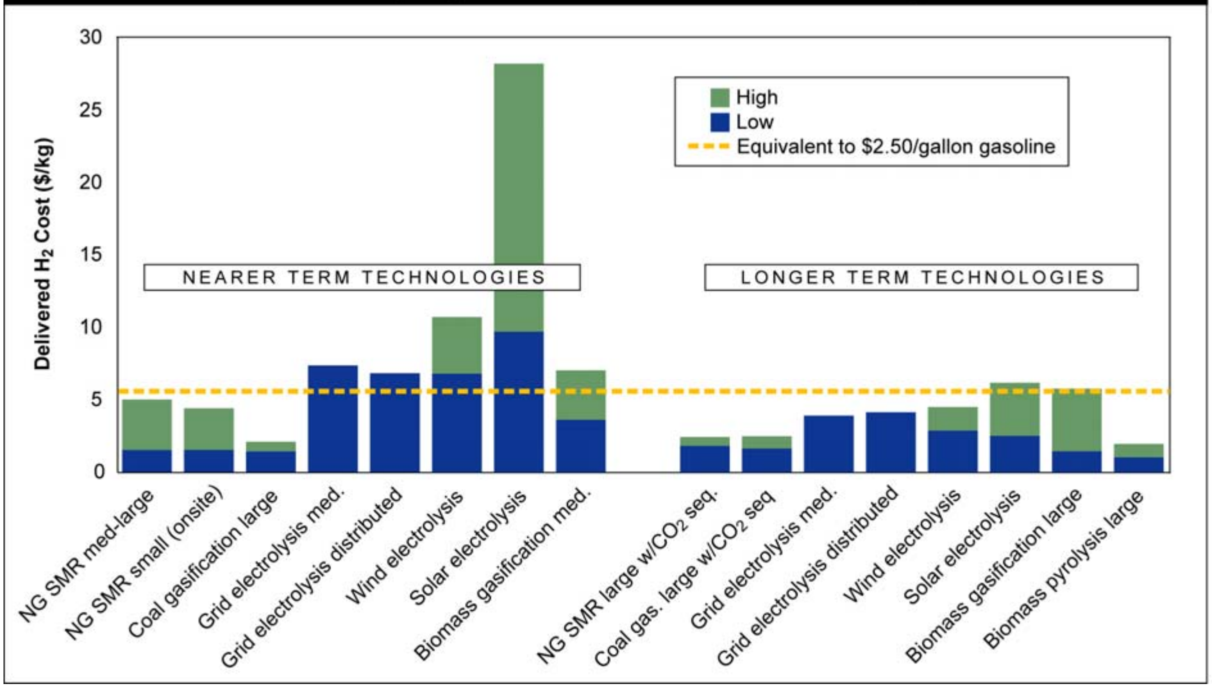
In its 2004 study, the National Academy of Sciences (NAS) identified a number of specific research and development priorities that could help bring the costs of renewably-produced hydrogen within the range of competitiveness with other vehicle fuel and hydrogen production options.[12] According to this study, priorities for wind power research and development include, first, enhancing performance at variable wind speeds and improving grid compatibility "through better turbine design and optimization of rotor blades, more efficient power electronic controls and drive trains, and better materials;" and second, optimizing wind-electrolysis-hydrogen systems by pursuing "integration opportunities…with respect to wind energy systems, electrolyzers, and hydrogen storage."[13]

Priorities for research and development of solar energy options for producing hydrogen include reducing near-term costs for thin-film solar cells, together with the mid- to longer-term development of organic polymer-based solar cells that can be mass produced at low cost.. The NAS study also mentions hydrogen production pathways that use light photons to directly split water molecules as a promising area for long-term research.[14] Finally, primary challenges for biomass-based hydrogen production include: (1) addressing "the low thermodynamic efficiency of biomass-to-hydrogen conversion, the high costs of bioenergy crop production and biomass gasification, and the significant demand for and impact on land use and natural resources for bioenergy crop farming," and (2) engineering microorganisms and processes for "direct photobiological hydrogen production without biomass as an intermediate."[15]

Figure 1 summarizes nearer- and longer-term estimates of the cost of hydrogen delivered through different production pathways, based on various studies. Clearly, substantial progress is needed to make environmentally sustainable hydrogen production pathways cost-competitive with petroleum fuels, even assuming that hydrogen-powered vehicles will be significantly more efficient than their conventional gasoline-powered counterparts.

Figure 1

Cost Estimates for Delivered Hydrogen from Different Production Pathways



Notes: The cost ranges shown are taken from many different sources and may include inconsistent assumptions with regard to production scale, interest rates, etc. The gap between the high and low estimates in each column tends to reflect the relative numbers of analyses available for each pathway, rather than inherent uncertainty about the costs for each pathway. Yellow line indicates the cut-off price of hydrogen below which it becomes competitive with a gallon of gasoline priced at $2.50/gallon. NG= natural gas, SMR=steam methane reformation.

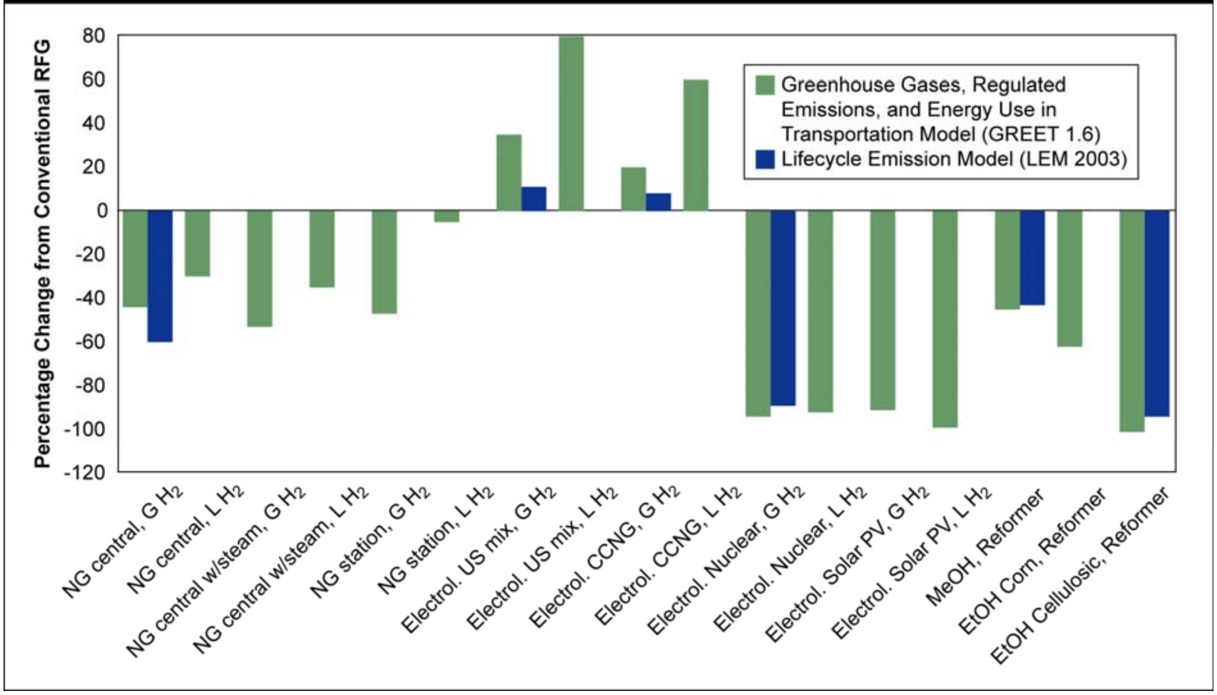
ENVIRONMENTAL IMPACTS OF DIFFERENT HYDROGEN PRODUCTION PATHWAYS

Besides cost, environmental considerations will also be important in choosing among various potential hydrogen production pathways. These considerations include not only global warming emissions, but also local pollutant emissions, soil and water quality impacts, and land, water, and other non-feedstock resource requirements.

The global warming and air pollutant impacts of various hydrogen production pathways have been reasonably well-studied, but other environmental considerations have been less well characterized. Additional studies are needed to better characterize the potential environmental impacts of hydrogen production—both generally and in terms of impacts on specific regions.

Figure 2

Global Warming Emissions from Hydrogen Fuel Cell Vehicle Refueling Pathways



Notes: GREET 1.6 is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. LEM 2003 is the Lifecycle Emission Model (see endnote 16). NG = natural gas; H2 = hydrogen; CCNG = combined cycle natural gas power plant; EtOH = ethanol; G = gaseous; L = liquid; MeOH = methanol; PV = photovoltaics; RFG = reformulated gasoline.

Figure 2 compares estimated full fuel-cycle global warming emissions for various hydrogen production and distribution pathways, assuming that hydrogen is used to operate a fuel cell vehicle. Emissions are shown relative to the full fuel-cycle emissions of a conventional vehicle running on reformulated gasoline.[16] The figure shows that different hydrogen production pathways have dramatically different effects on global warming emissions. If liquid hydrogen is produced via electrolysis using conventional grid power (and assuming the U.S. average electric generating mix), estimated full fuel-cycle emissions for a given number of miles traveled are as much as 80 percent higher than those associated with a conventional gasoline vehicle. If, on the other hand, hydrogen is produced using biomass or other renewable resources, full fuel-cycle emissions can be reduced by as much as 100 percent—implying that net emissions in absolute terms are at or near zero.

Figure 2 does not, however, address an additional, important consideration in weighing the relative global warming benefits of renewably-produced hydrogen: that is, whether renewable energy would instead be better used to displace other sources of electricity. In fact, a number of studies have concluded that using wind or solar power to displace coal use in the electricity sector produces significantly larger global warming benefits than if the same energy is used to make hydrogen as a means of displacing gasoline use in the transportation sector. For example, one recent analysis found that using wind energy to displace marginal electricity generation in California would produce global warming emissions reductions of about 640 grams per kilowatt-hour (kWh).[17] By comparison, using the same electricity to produce hydrogen via electrolysis for use in a fuel cell vehicle would result in reductions of about 470 grams per kWh. The disparity would be much greater if the wind power were used to displace coal-fired electricity generation, which typically produces global warming emissions of as much as 1,100 grams per kWh; on the other hand, benefits are roughly comparable in the case where wind power replaces modern, efficient combined cycle natural gas generation.

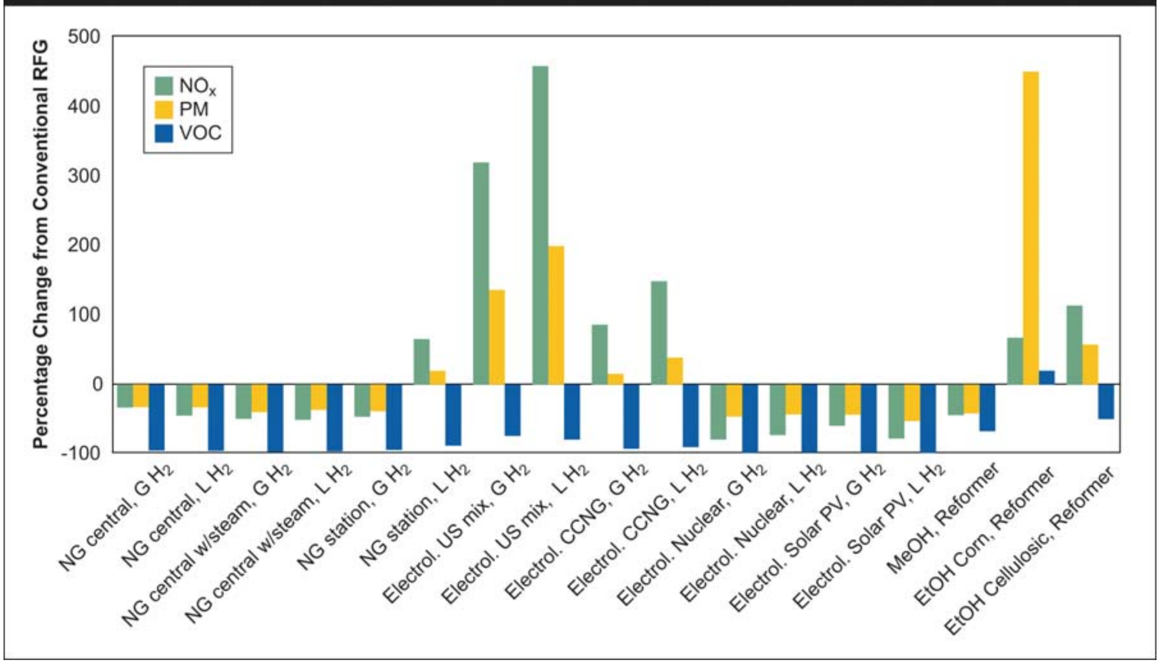
The calculation changes, of course, at times when renewable energy is available but not in a position to displace conventional power generation. Wind power, for example, is sometimes available during off-peak hours when the marginal system generator is a baseload power plant. Often baseload plants, for both economic and environmental reasons, cannot readily ramp down their output to accommodate production from other generators. In these instances, using excess wind power that cannot be absorbed by the grid to produce hydrogen for vehicles would result in additional pollution benefits, regardless of the theoretical advantages of displacing conventional power generation. Hydrogen production under these circumstances provides a form of energy storage that can help to offset the limitations of intermittent renewable resources from a grid perspective. In sum, renewably-generated electricity is likely to produce maximum benefits if it is used to directly displace marginal fossil power plants, such as natural gas peaker or mid-peaker plants, or—wherever possible—coal plants. In other instances, its use for hydrogen production may or may not produce substantial overall benefits relative to supplying power directly to the electricity grid.

As with global warming emissions, the air pollutant emissions and soil and water impacts associated with different hydrogen production and distribution pathways can also vary widely. Moreover—in contrast to global warming emissions which affect the atmosphere equally no matter where they are emitted—other types of environmental impacts often have important local and regional dimensions. The fact that the public health impacts of air pollutant emissions depend in part on the size of the exposed population, for example, adds considerable uncertainty regarding this class of potential impacts.

Figure 3 compares the estimated full fuel-cycle emissions of major air pollutants for the same hydrogen production and distribution pathways shown in Figure 2. As before, the comparison is between a vehicle operating on a hydrogen fuel cell and a vehicle operating on reformulated gasoline. The figure suggests that most hydrogen production pathways produce significant air quality benefits. The significant exceptions involve electrolysis using average grid power or combined cycle natural gas plants and ethanol-based pathways—all of which produce significant increases in emissions of nitrogen oxides (NOx) and particulate matter (PM).[18]

Figure 3

Air Pollutant Emissions from Hydrogen Fuel Cell Vehicle Refueling Pathways



Source: GREET Model 1.6.[19]
Notes: NOx = nitrogen oxides; PM = fine particulate matter with diameter less than 10 microns; VOC = volatile organic compounds; NG = natural gas; H2 = hydrogen; CCNG = combined cycle natural gas power plant; EtOH = ethanol; G = gaseous; L = liquid; MeOH = methanol; PV = photovoltaic; RFG = reformulated gasoline.

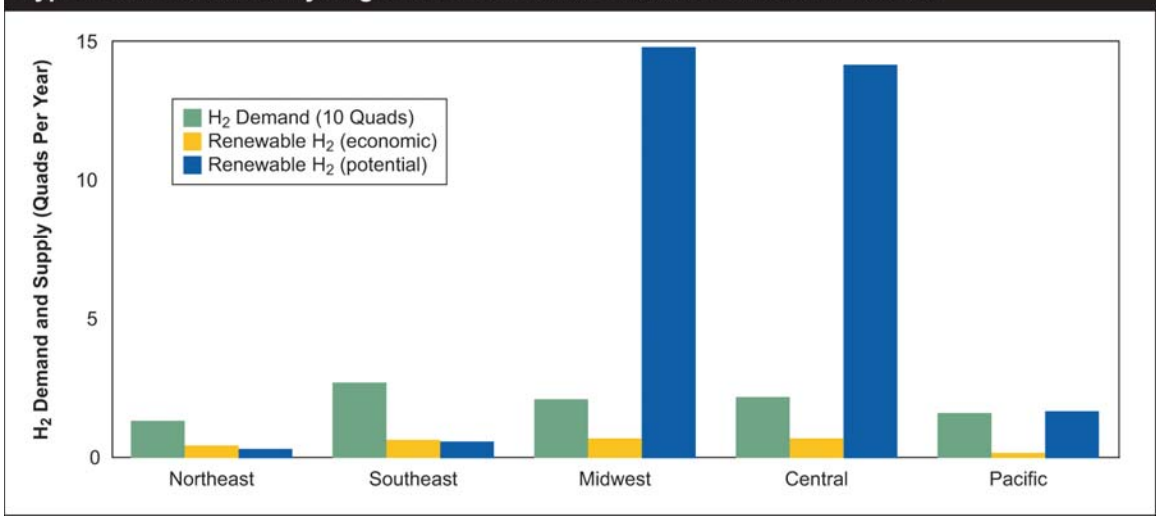
RENEWABLE HYDROGEN POTENTIAL IN THE UNITED STATES

The potential renewable resource base for producing hydrogen in the United States is theoretically very large. According to one estimate, the quantity of hydrogen that could be produced domestically using solely renewable resources could more than offset the current petroleum consumption by the U.S. transportation sector on an energy basis.[20] Much of this potential, however, is based on wind and solar resources that are unlikely to become economically competitive, except perhaps in the very long term (i.e., mid-century or later). Renewable sources of hydrogen that are likely to be less costly in the nearer term include dedicated energy crops, municipal solid waste, agricultural and livestock residues, and certain wind resources that are located close enough to demand centers to be relatively attractive.

Figure 4 presents a hypothetical regional supply and demand picture for renewable hydrogen production in the year 2040. The left-most bar in each cluster represents regional hydrogen demand assuming that: (1) overall hydrogen demand reaches a level equivalent, in energy terms, to displacing one-third of current U.S. transportation sector petroleum consumption and (2) each region's share of the latter total is proportional to its current share of national gasoline consumption.[21] The middle bar in each cluster—labeled "Renewable H2 (economic)"—corresponds to an estimate of the amount of hydrogen that would be available to each region by 2040 at a delivered cost of $3 per kg or less. Most of this economic potential consists of hydrogen produced using biomass wastes and relatively low-cost wind power. As noted previously, the $3 per kg cost threshold is approximately equivalent, on a per-mile basis, to gasoline at $1.50 per gallon, assuming that the hydrogen is used in fuel cell vehicles that are twice as efficient, on average, as conventional vehicles. The right-most bar in each cluster—labeled "Renewable H2 (potential)"—corresponds to estimates of the full theoretical potential for hydrogen production in each region by 2040. Summing across all regions, the total national potential for renewable hydrogen production is estimated to be about 30 quads. Note that in some cases, the middle bar for a particular region (economic H2 potential) includes access to hydrogen produced in other regions—this explains why economic potential slightly exceeds theoretical production potential in the Northeast and Southeast.

Figure 4

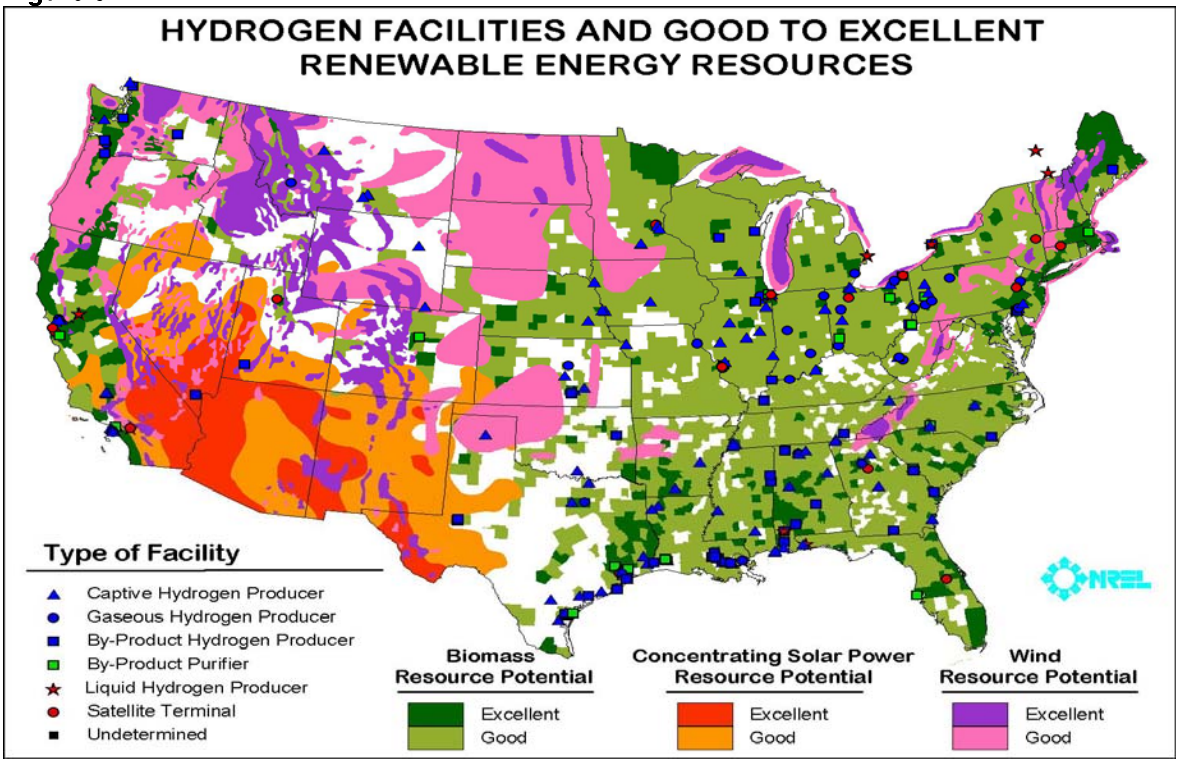
Hypothetical 2040 U.S. Hydrogen Demand and Renewable Production Potential



Source: Meyers et al. (2003) with additional analysis by Lipman.
Notes: "Northeast" includes CT, ME, MA, NH, NJ, NY, PA, RI, and VT; "Southeast" includes AL, DE, FL, GA, KY, MD, MI, NC, SC, TN VA, and WV; "Midwest" includes IA, IL, IN, KS, MI, MN, MO, NB, ND, OH, SD, and WI; "Central" includes AR, AZ, CO, ID, LA, MT, NV, NM, OK, TX, UT, and WY; "Pacific" includes AK, CA, HI, OR, and WA. Note that HI and AK were included in demand estimates for the Pacific region, but NOT in the estimate of overall production potential for this region.

The regional estimates presented in Figure 4 suggest that the potential for renewable hydrogen production is particularly large in the Midwest and Central states. This is a result of substantial biomass resource potential from waste streams and dedicated energy crops. These areas also have significant wind power resources that could be used to produce hydrogen, albeit at somewhat higher cost. Other regions have more modest renewable hydrogen production potential. Potential resources in the Northeast and Southeast are largely biomass-based, as they are in the Midwest and Central states, although the Northeast also has potentially significant wind resources. By comparison, much of the renewable hydrogen production potential in the Pacific region occurs in the form of solar and wind powered electrolysis, both of which entail comparatively high costs. The map shown in Figure 5 describes the overall distribution of potential wind, solar, and biomass resources for producing hydrogen across the United States.

Figure 5



Source: National Renewable Energy Laboratory (www.nrel.gov)

INFRASTRUCTURE AND TECHNOLOGICAL CONCERNS FOR A POTENTIAL TRANSITION TO A HYDROGEN ECONOMY

Significant technological and cost hurdles must still be overcome before hydrogen can play a major role in the nation's energy economy and before truly sustainable hydrogen production pathways become competitive with fossil fuel-based production pathways, much less conventional transportation fuels. Given the potential promise of hydrogen as a long-term energy option, continued investment to overcome these hurdles and to advance hydrogen and fuel cell technologies while developing clean hydrogen production pathways is warranted. These investments must, however, occur in conjunction with aggressive near-term actions to mobilize other, already available technologies for reducing global warming emissions and oil dependence.

The public sector will almost certainly need to play a major role in the earlier stages of developing a hydrogen-based economy. Given that most hydrogen technologies are still at a relatively early stage of development, government assistance in the form of R&D funding, early deployment incentives, and public/private partnerships are all likely to be needed in giving hydrogen an opportunity to compete in the marketplace against cheaper and more established incumbent energy systems. As field experience and technological innovation reduce the costs and improve the performance of hydrogen production, distribution, and end-use technologies, the public sector role can diminish and the private sector can assume a greater share of the burden of developing the hydrogen infrastructure. Meanwhile, promoting other short- and long-term solutions to America's energy problems also requires significant public sector action. We return to policy recommendations in the concluding section of this report, but urgent priorities here include setting performance standards that require auto manufacturers to introduce vehicles with lower carbon emissions or better fuel economy (or both); accelerating the deployment of off-the-shelf and near-commercial efficiency and low-carbon technologies; and establishing enforceable limits on global warming emissions.

Public sector leadership in the early stages of a potential hydrogen transition provides an opportunity for policymakers to promote hydrogen production pathways that minimize long-term social costs. Thus, federal, state, and local efforts to promote hydrogen through production incentives or tax breaks must be designed to favor those hydrogen sources and production pathways that rely on clean and climate-friendly resources and that promise to be compatible with long-term energy security and environmental objectives. Finally, if hydrogen is to have a future that minimizes cost and maximizes the odds of success, policy makers will need to consider a number of additional issues, all of which are closely related to the optimal choice of hydrogen production pathways.

The need for new infrastructure to produce, store, and distribute hydrogen, for example, is likely to be a key issue in any future transition to a hydrogen economy. In the early years of such a potential transition, distributed production using small-scale reformers and electrolyzers, coupled with some mobile vehicle refueler capacity and liquid hydrogen delivery by truck, would appear to offer a number of advantages. Once hydrogen demand reaches the scale and level of concentration needed to justify pipeline delivery, the development of larger-scale production facilities could be pursued, potentially in combination with carbon capture and storage.

The optimal design and development of infrastructure for distributing and dispensing hydrogen would also depend on the technology used to store hydrogen on board vehicles. As was highlighted by the 2004 NAS report referenced previously, further progress in developing such technologies is essential if hydrogen-powered vehicles are to become practical. While most current hydrogen vehicle prototypes carry hydrogen in compressed gas form, this approach suffers from bulkiness, requires significant electricity inputs to compress the hydrogen, and raises potential safety concerns due to the high storage pressures involved. Other on-board storage systems, such as those based on metal and alkaline hydrides, cryogenic liquid hydrogen, and carbon nanotubes, are under development. Thus, careful attention would need to be paid to the interplay between hydrogen production, hydrogen distribution, and hydrogen storage aboard vehicles in any potential transition to a hydrogen economy. Managing this transition would be further complicated by the existence of numerous technology options and the potential for future breakthroughs, especially with regard to hydrogen storage alternatives.

Meanwhile, solving the problem of on-board fuel storage is only one of several technological hurdles that stand in the way of commercializing hydrogen-powered vehicles. After nearly four decades and billions of dollars of research investment, significant issues remain with respect to the cost and durability of fuel cells in automotive applications. According to the 2004 NAS study:

> "The challenge is to develop automotive fuel cell systems that are lightweight and compact (i.e., have high power densities by both mass and volume), tolerant to rapid cycling and on-road vibration, reliable for 4000 to 5000 hours or so of noncontinuous use in cold and hot weather,

> and able to respond rapidly to transient demand for power (perhaps by being hybridized with a battery or ultracapacitor for electrical storage on the vehicle), and able to use hydrogen of varying purity."[22]

The proton exchange membrane (PEM) type fuel cell technology that has emerged as most likely to be suited for automotive applications does not yet meet these criteria; indeed, the cost of fuel cell prototypes for light-duty vehicles remains a factor of 10 to 20 times too expensive, according to the NAS study.[23] The larger technology challenge is, moreover, compounded by a timing challenge: any future commercialization of hydrogen fuel cell vehicles would need to be coordinated with the deployment of a supporting hydrogen distribution infrastructure. On the one hand, a broadly dispersed refueling infrastructure is necessary if hydrogen vehicles are to achieve significant market penetration beyond centralized fleet applications. On the other hand, such infrastructure investments risk substantial stranded assets if the commercialization of hydrogen vehicles fails to materialize for some reason, or materializes much more slowly than expected.

In light of these difficulties, the fact that other petroleum alternatives present less daunting infrastructure and technology challenges suggests that a large-scale transition to hydrogen is not only unlikely in the near-term, but far from inevitable even in the longer run. For example, low- or no-carbon cellulosic ethanol made from agricultural waste or low-impact energy crops would have the distinct advantage of being more compatible not only with existing infrastructure for distributing and dispensing liquid fuels, but also with existing on-board fuel storage technologies. Similarly, future all-electric or plug-in hybrid vehicles could be recharged directly from the existing electricity grid. Finally—and perhaps most importantly in terms of immediate policy priorities—already available hybrid-electric and conventional technologies offer the potential to substantially boost vehicle efficiency and reduce global warming emissions in the very near term while requiring no new infrastructure or automotive technology breakthroughs whatsoever.

CONCLUSION AND POLICY RECOMMENDATIONS

The results of this preliminary assessment highlight a number of significant issues that must be resolved before hydrogen can play a substantial role in addressing the nation's and the world's energy security and global warming challenges. Central among these is the fact that the least expensive and most mature hydrogen production pathways available at present are not necessarily environmentally sustainable. For example, one of the cheaper options available today—producing hydrogen from coal—will not be acceptable unless associated global warming, air pollution, and mining impacts are successfully addressed. The deployment of coal gasification technology with carbon capture and storage, in combination with mining practices that minimize land and water impacts, could allow coal to become a sustainable and abundant source of hydrogen over the long term, both in the United States and in other coal-rich countries. However, further aggressive deployment of advanced coal gasification technologies, in combination with carbon capture and storage, is needed to better determine the cost, feasibility, and effectiveness of this potential hydrogen production pathway.

Hydrogen production from natural gas, meanwhile, offers a number of near-term advantages in terms of cost and technological maturity, but it too can prove problematic as a longer-term solution. Because natural gas, like coal, is a fossil fuel, its use as a hydrogen feedstock generates pollutant emissions that contribute to global warming and air quality problems. Data presented in this report (see Figure 2) indicate that per-mile global warming emissions for a fuel cell vehicle running on hydrogen produced using various forms of steam methane reformation are anywhere from 40 percent to 50 percent lower than emissions for a conventional vehicle running on reformulated gasoline. These emissions reductions are not trivial—but it is also the case that comparable global warming benefits could be achieved by simply deploying efficient hybrid-electric and conventional technologies that are already available today. Moreover, high natural gas prices and supply constraints have recently emerged as serious issues that show no signs of being resolved soon, at least in North America.

Thus, natural gas is probably best thought of as a potential transition fuel to cleaner, low-carbon, domestic hydrogen production options, such as renewables or coal with carbon capture and storage. Given the extensive natural gas infrastructure that already exists, use of this feedstock may make sense in the early stages of a possible future shift to hydrogen but even then, natural gas should only be considered in the context of an alternative longer-term hydrogen production strategy, with care taken to address technological lock-in concerns, wherein an inappropriate technology is deployed too early, thereby preventing a better technology from emerging as the longer term solution. Additionally, distributed production from natural gas using small-scale steam methane reformers—because it obviates the need for hydrogen transport—is also an attractive short-term production option, but it is important to keep in mind that this option does not easily allow for eventual carbon capture and storage. Meanwhile, to alleviate supply constraints that might otherwise preclude the use of natural gas as a transition fuel for producing hydrogen, natural gas demand growth should be addressed through improvements in the end-use efficiency of gas equipment; and through the increased use of combined heat and power and other distributed or high-efficiency technologies.

Compared to coal- or natural gas-based production pathways, hydrogen from nuclear energy could offer some advantages in terms of global warming emissions. However, cost estimates of hydrogen production at future centralized, large-scale nuclear plants remain very uncertain and would also entail high distribution costs. Furthermore, the nuclear production pathway faces critical and probably overwhelming hurdles in terms of safety, waste management and disposal, capital costs, and public acceptance. In short, any near-term expansion of nuclear capacity in the United States appears unlikely at this time, although some level of research and development into nuclear-based options for producing hydrogen may be justified based on the long-term potential of this technology if current waste and safety concerns can be addressed.

Given the shorter- and longer-term problems with conventional coal, natural gas, and nuclear production pathways, renewably-generated hydrogen and perhaps coal gasification with carbon capture and storage emerge as the strongest contenders for a fully sustainable solution. In particular, hydrogen from renewable resources offers multiple benefits in terms of energy security, fuel diversity, and reduced global warming emissions. Accordingly, strategies that emphasize renewable feedstocks and decentralized production (to reduce distribution costs and energy penalties) and that are compatible with the renewable resource base that exists in different regions may be critical to maximizing the potential benefits of a large-scale, sustainable transition to hydrogen. Electrolyzer and solar photovoltaic costs remain key issues for electrolysis-based renewable options, but other production methods that use biomass feedstocks are promising and offer a range of potential advantages.

In sum, hydrogen does indeed hold considerable promise as a potentially clean and ample energy option that could eventually play a major role in addressing multiple public policy objectives, from improving energy security to reducing global warming risks. That promise will only be realized, however, if—in the long run—hydrogen is largely produced from renewable resources and potentially also from non-renewable technologies that include carbon capture and storage. Unfortunately, commercial-scale development of hydrogen production and distribution systems as well as mass production of fuel cell vehicles and other hydrogen end-use technologies remains more than one, and probably several, decades off, while the time required to make certain renewable production pathways cost-competitive may be longer still.

As a result, hydrogen is not in a position to solve America's energy problems any time soon. And in the meantime, doing nothing to curb global warming or cut oil dependence until a hydrogen economy is ready is not acceptable. A responsible, economically sensible energy policy requires a comprehensive approach that emphasizes both near-term results and investment in long-term solutions. Specifically, the United States must act now to implement the following policies:

- Adopt near-term performance standards that require automakers to cut the oil consumption and global warming pollution of their fleets by deploying technologies that reduce carbon emissions, save fuel, or do both.[24]

- Accelerate deployment of off-the-shelf and near-term vehicle technologies and fuels (such as hybrid electric vehicles and biofuels like cellulosic ethanol) that can reduce oil dependence and global warming pollution while providing a potential transition to hydrogen fuel cells.

- Promote the strategic deployment of fuel cells over the next decade, including conducting fleet testing of fuel cell vehicles in the nation's smoggiest cities to acquire real-world experience with commercialization challenges while also achieving immediate air quality benefits.

- Support continued research and development into fuel cell vehicle technology and advanced hydrogen system technologies, complemented with research, development, and deployment efforts targeted at producing hydrogen from wind, solar, and biomass resources and from fossil-fuel sources with carbon capture and storage. These are the most sustainable options for potential future hydrogen production.

- Support long-term research and development efforts to continue exploring clean-energy alternatives to hydrogen such as biofuels, plug-in hybrids, and battery electric vehicles.

ENDNOTES

[1] This briefing paper draws heavily from *What Will Power the Hydrogen Economy? Present and Future Sources of Hydrogen Energy*, a longer paper prepared for the Natural Resources Defense Council (NRDC) by Timothy E. Lipman of the University of California Berkeley's Institute of Transportation Studies. The full Lipman report was published in July 2004 and is available at http://www.its.ucdavis.edu/publications. Other relevant NRDC documents, including a position paper on hydrogen ("Is Hydrogen the Solution?") and a report on America's oil dependence (*Dangerous Addiction*) are available at www.nrdc.org.
[2] National Research Council and National Academy of Engineering of the National Academy of Sciences, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, D.C., February 2004.
[3] Lashof, Daniel and Roland Hwang, *Dangerous Addiction 2003: Breaking the Chain of Oil Dependence*, NRDC, March 2003, p. 5.
[4] Ibid.
[5] Such standards include raising vehicle fuel economy standards to 40 miles per gallon for light trucks and cars, and reducing our oil consumption by at least 2.5 million barrels per day by 2015, and 10 million barrels per day by 2025.
[6] Freund, F., J.T. Dickinson, and M. Cash, "Hydrogen in Rocks: An Energy Source for Deep Microbial Communities," *Astrobiology* 2(1): 83-92, 2002.
[7] Longer-term options for hydrogen distribution and supply may include more futuristic concepts such as delivering hydrogen along with electricity by using it as the cooling fluid for superconductive transmission systems. See Gehl, S. and D. Rastler, "Evolving Energy Delivery Systems Using Distributed Resources," Electronic Presentation, Electric Power Research Institute, Palo Alto, CA, 2001.
[8] A more complete discussion of these assumptions, together with separate estimates for on-site hydrogen production costs (i.e., without added distribution costs) can be found in the longer paper from which this review is derived (see Endnote 1).
[9] This cost range assumes natural gas prices ranging from $3–$6 per gigajoule (GJ). The low end of this range — $3/GJ — is well below current prices for natural gas, which have increased sharply in recent years and which now typically range from $5–$7 per GJ in different parts of the country. Hence, a delivered hydrogen cost of $2/kg would be considered optimistic for steam methane reformation given current natural gas prices, while costs of $3–$5 per kg would likely be more realistic. Production scale and delivery mechanism/distance are, of course, also important factors in determining final hydrogen production costs.
[10] This option is, of course, predicated on the availability of cost-effective means of storing hydrogen. Underground caverns can provide the most economical means of storing hydrogen (with costs on the order of $0.10-0.20 per kg) but suitable caverns exist only in some locations. Storing hydrogen as a compressed gas or liquid is the next most economical approach with costs ranging from $0.30-$2.00 per kg, depending on flow rates and storage duration. A last option, metal hydride storage, is only competitive for low flow rates and short storage times. See: Mann, M.K., P.L. Spath, and W.A. Amos, "Techno-economic Analysis of Different Options for the Production of Hydrogen from Sunlight, Wind, and Biomass," *Proceedings of the 1998 U.S. DOE Hydrogen Program Review,* NREL/CP-570-25315, 1998.
[11] M.K. Mann and R.P. Overend, "Hydrogen from Biomass: Prospective Resources, Technologies, and Economics," National Renewable Energy Laboratory, Presentation to National Academy of Sciences Committee, January 22, 2003.
[12] National Research Council, 2004.
[13] Ibid, p. 100.
[14] Ibid, p. 104.
[15] Ibid, p. 103.
[16] Estimates of full fuel-cycle emissions shown in the figure come from two well-known models: the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Lab and the Lifecycle Emission Model (LEM) developed at U.C. Davis. (See: Argonne National Laboratory, *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*,

ANL/ESD/TM-163, June 2001, and Delucchi, M.A., *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials*, UCD-ITS-RR-03-04, Institute of Transportation Studies, University of California, Davis, June 2003.) Both models account for emissions of global warming pollutants other than CO_2; these emissions are included in the final results on a CO_2-equivalent basis.

[17] Lipman, T.E., R. Ramos, and D.M. Kammen, *An Assessment of Battery and Hydrogen Energy Storage Systems Integrated with Wind Energy Resources in California*. California Energy Commission, PIER Energy-Related Environmental Research, 500-02-04, 2004.

[18] Further detail concerning these estimates may be found in ANL (2001). In addition, DeLucchi (2003) and Contadini (2002) have analyzed air pollution impacts from different hydrogen production pathways. (See Endnote 16, above, for the ANL and DeLucchi citations and Contadini, J., *Life Cycle Assessment of Fuel Cell Vehicles - Dealing with Uncertainties*, UCD-ITS-RR-02-07 Institute of Transportation Studies, University of California, Davis, May 2002.)

[19] ANL, 2001.

[20] Meyers, D.B., G.D. Ariff, B.D. James, and R.C. Kuhn, *Hydrogen from Renewable Energy Sources: Pathway to 10 Quads For Transportation Uses in 2030 to 2050*, Draft Report for U.S. DOE under Grant No. DE-FG01-99EE35099, Directed Technologies, Inc., February 2003.

[21] Current petroleum consumption by the U.S. transport sector equals about 27 Quads. The assumption here is that overall hydrogen demand has grown to about 10 Quads (10.5 exajoules) by 2040.

[22] National Research Council, 2004, p. 26.

[23] Ibid, p. 35.

[24] See note 5.