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A Hydrogen Economy and Fuel Cells: An Overview

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Summary

There is growing interest in the use of hydrogen as the main fuel for stationary, mobile, and transportation applications, especially using fuel cells. This is particularly true in light of the Bush Administration's efforts to increase research and development for these technologies. In his January 2003 State of the Union Address, President Bush announced a new, five-year research initiative on hydrogen fuel and fuel cells. This effort is a key component of the Administration's proposed energy policy.

Policymakers are interested in hydrogen and fuel cells because they could potentially lead to significant societal benefits. Depending on how the fuel is produced and distributed, hydrogen fuel and fuel cells could help significantly reduce pollution and greenhouse gas emissions. Further, if hydrogen were produced using domestic energy supplies, it could help reduce dependence on imported petroleum. Also, fuel cells could be used to improve the efficiency and reliability of electricity generation.

However, there are some key barriers to the development of a "hydrogen economy." Most importantly, the current cost of both fuel cells and hydrogen fuel makes them uncompetitive for most applications. Reducing these barriers is one of the driving factors in the government's involvement in hydrogen and fuel cell research and development. But this involvement raises concerns, including the cost of such research and the possibility of the government "picking winners" among competing technologies.

This report discusses six key questions related to the hydrogen economy and fuel cells: 1) what is hydrogen fuel; 2) what is a fuel cell; 3) how will hydrogen fuel be used; 4) where will hydrogen fuel come from; 5) what would it mean to move to a hydrogen economy; and 6) what role can Congress play. This report will be updated annually, or as events warrant.

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Hydrogen is a chemical that can be produced using any primary energy source. Its use as a fuel could lead to lower emissions of pollutants and greenhouse gases. Further, depending on which primary energy supply is used, hydrogen fuel could help reduce energy imports, especially for transportation. A major use of hydrogen would be in fuel cells. A fuel cell is a device that produces electricity through a chemical process, as opposed to combustion. Fuel cells have the potential to achieve significantly higher efficiencies (i.e. produce more power for a given energy input) than combustion engines[1] and conventional power plants.

The prospect of hydrogen becoming the main fuel for all energy-related applications, a "hydrogen economy," and the continuing development of fuel cells to utilize hydrogen fuel has generated growing interest within the policy realm. This is especially true after two key initiatives by the Bush Administration:[2] the FreedomCAR initiative to promote cooperative research and development between the federal government and the major American automakers on fuel cell vehicles; and the President's Hydrogen Fuel Initiative to promote federal research and development on hydrogen fuel and non-automotive fuel cell technology.

This push for research on hydrogen and fuel cells has led to some basic questions about the function and use of the new technologies. Six key questions related to a hydrogen economy and fuel cells are:

- What is hydrogen fuel?
- What is a fuel cell?
- How will hydrogen fuel be used?
- Where will hydrogen fuel come from?
- What would it mean to move to a hydrogen economy?
- What role can Congress play?

What is hydrogen fuel? A fuel is any high energy substance that can be consumed to produce useful work. Examples include gasoline used to propel an automobile and coal used to generate electricity at a power plant. Hydrogen can also be used as a fuel, and is the most abundant element in the universe. However, hydrogen is not a primary fuel. That is, it does not occur naturally but instead is found most often as part of a larger molecule, such as water or petroleum. Today,

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[1]For more information on transportation fuel cell applications, see CRS Report RL30484, *Advanced Vehicle Technologies: Energy, Environment, and Development Issues.*

[2]For more information on these initiatives, see CRS Report RS21442, *Hydrogen and Fuel Cell Vehicle R&D: FreedomCAR and the President's Hydrogen Fuel Initiative.*

most hydrogen is extracted by processing (reforming) methane (natural gas) at oil refineries and chemical plants.[3] However, in the future hydrogen could potentially find widespread use as a fuel, either burned in combustion engines or combined with oxygen in fuel cells.[4] Both methods produce useful energy, either as motion or electricity, and both generate waste.[5]

To produce hydrogen fuel, two key components are necessary: energy and hydrogen atoms. In some cases, for example using natural gas, both components are supplied simultaneously as hydrogen atoms are separated from the methane molecule. In other cases, the two components are supplied separately. For example, electricity can be used to separate hydrogen from water to generate hydrogen fuel.[6]

What is a fuel cell? A fuel cell is an electrochemical device that uses hydrogen (or a hydrogen-rich fuel) and oxygen to produce electricity.[7] It is physically and chemically similar to a battery, but as the name implies, fuel cells make use of an input fuel. They can be refueled at any time, and do not run down or need to be recharged, making them similar to combustion engines in their use. However, fuel cells utilize chemical processes that are inherently more efficient than combustion. For example, a typical combustion-based fossil fuel power plant operates at about 35% efficiency,[8] while a fuel cell electricity generator can operate at 40 to 60% efficiency.[9] As such, fuel cells could potentially provide energy more cleanly and efficiently than combustion engines.

There are many varieties of fuel cells, but they are all related by a single common chemistry. One type of fuel cell, a polymer electrolyte membrane (PEM) cell, is shown in **Figure 1**.[10] All fuel cells have three basic components: (1) an

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[3]The majority of this hydrogen is used by the refiner or chemical company onsite in the production of other chemicals. For example, hydrogen is used at refineries to remove sulfur from gasoline and diesel fuel.

[4] For more on hydrogen fuel, see [http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/]. Accessed November 13, 2003.

[5]U.S. Department of Energy (DOE), *Fuel Cell Report to Congress.* February 2003.

[6]These processes are explained further in the section "Where will hydrogen fuel come from?"

[7]DOE, *How Fuel Cells Work.* http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/how.html. Accessed November 13, 2003.

[8]Approximately 35% of the chemical energy contained in the fuel is converted into electrical energy. The remainder is lost as waste heat.

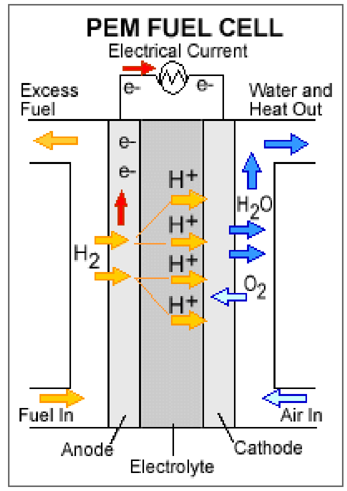
[9]If electricity and useful heat are generated simultaneously (cogeneration), efficiencies can reach 85%. U.S. Department of Energy, "Why Are Hydrogen and Fuel Cells Important?" [http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/why.html]

[10]Downloaded on November 13 from the Department of Energy, Energy Efficiency and Renewable Energy website.

(continued...)

anode, (2) a cathode, and (3) an electrolyte that separates them. The hydrogen fuel flows to the anode, where the electrons are removed and shuttled to the cathode through an external circuit to produce electricity. Oxygen (or another oxidant) is used at the cathode. When the oxygen, the positively charged hydrogen, and the electrons combine, water and heat are generated as waste, and the process is complete. The location of this chemical combination within the fuel cell, and the exact details of the chemical process vary with the type of fuel cell. However, all types generate electricity by first isolating the hydrogen from the oxygen, and then requiring electrons to flow through an external circuit before these three components combine.[11]

Figure 1. A Basic Fuel Cell



The power output from a single cell is relatively low. However, fuel cells are usually arranged in "stacks" to provide the necessary voltage to power a building or a car. Because of this, fuel cells can be sized to power any application, from a small cell phone to a large power plant.

While most fuel cells operate on pure hydrogen, some cells can operate on hydrogen-rich (hydrocarbon) fuels. One example is a direct methanol fuel cell (DMFC), which feeds methanol directly into the cell. In this case, the cell emits carbon dioxide and potentially other compounds, as well as water and heat. Hydrogen fuel cells can also be operated on other hydrocarbon fuels (including gasoline and natural gas) if a reformer is used along with the fuel cell. A reformer acts as a mini-refinery to separate the hydrogen from the other elements in the fuel. The use of a reformer or a direct methanol fuel cell could eliminate concerns over hydrogen production and storage, but would result in higher in-use emissions, compared to a hydrogen fuel cell.[12]

How will hydrogen fuel be used? Fuel cells and hydrogen could potentially meet any energy requirement. While some fuel cell systems are commercially available today, most applications are still under development. For example, fuel cell electrical power generation is presently in use in commercially available backup power applications, but the most advanced automotive fuel cells are still in the prototype stage. Fuel cell automobiles, trucks, and buses are being demonstrated worldwide, but at present are very expensive. Further, fuel cells are being studied for smaller, mobile applications such as notebook computers and cell phones. In addition to fuel cell applications, hydrogen fuel can be combusted in

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[10](...continued)
http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/types.html

[11] For more information on fuel cells, see [http://fuelcells.si.edu/index.htm] and [http://www.fuelcells.org/whatis.htm].

[12] Depending on the efficiency of the reformer and fuel cell, as well as the characteristics of the fuel used, even using a reformer (as opposed to pure hydrogen) a fuel cell system can achieve lower overall emissions than conventional systems.

specially designed automobile engines or power generation systems, although currently the advantages of fuel cells appear to outweigh those of hydrogen combustion.

There are several fuel cell technologies currently in various stages of development. The demands of a particular application generally determine the choice of technology to be applied.[13] For example, phosphoric acid fuel cells are commercially available today, mainly in larger stationary power generation applications. However, these fuel cells operate at relatively high temperatures (from 300 to 400 degrees F) , so they are not practical in many applications. Proton exchange membrane (PEM) fuel cells operate at relatively low temperatures (around 175 degrees F) and can vary their output quickly. PEM technology is seen as the most likely fuel cell for automotive applications. Other types include molten carbonate, solid oxide, and alkaline fuel cells. Each of the various types faces technical barriers that include cost,[14] fuel supply,[15] and durability.

Where will hydrogen fuel come from? Several factors will affect future supplies of hydrogen. As stated above, hydrogen itself is not a primary energy source, and must be generated using energy and a supply of hydrogen atoms.[16] In addition to production issues, there are concerns over supplying hydrogen to end-users, as there is little current infrastructure for hydrogen fuel storage and distribution.

Sources of hydrogen. One key advantage of using hydrogen as a fuel is that virtually any primary energy source can be used to generate it. (See **Figure 2**.[17]) A major motivation for the hydrogen economy is the potential to use environmentally benign, domestic, and/or sustainable energy sources. Hydrogen can be produced either by reforming hydrocarbon fuels or by splitting water.

Hydrocarbon fuels include fossil fuels (crude oil, coal, and natural gas) and biomass such as alcohol (e.g. methanol produced from landfill methane or ethanol produced from corn). Hydrocarbons must be reformed to produce hydrogen. This is significantly more expensive than using gasoline directly. According to one producer's analysis, in automotive applications, hydrogen reformed from natural gas is projected to cost roughly twice as much as gasoline at the pump.[18] Further, this

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[13]For more information on the many applications currently being tested, see [http://www.fuelcells.org/charts.htm]. For more information on the types of fuel cells, see [http://www.fuelcells.org/fctypes.htm].

[14] One major contributor to cost is raw materials such as precious metals (e.g. platinum) which are used as catalysts.

[15] Some cells require extremely pure fuel.

[16] In certain applications, hydrogen may not be the most suitable fuel. Instead, a hydrogen-rich primary fuel may be appropriate for direct use in the fuel cell.

[17] Reproduced with permission from General Motors Corporation.

[18] Hydrogen produced from natural gas is projected to cost roughly 8 cents per mile, as opposed to 4 cents per mile for gasoline. Cost per mile estimates from "Long-Term Energy

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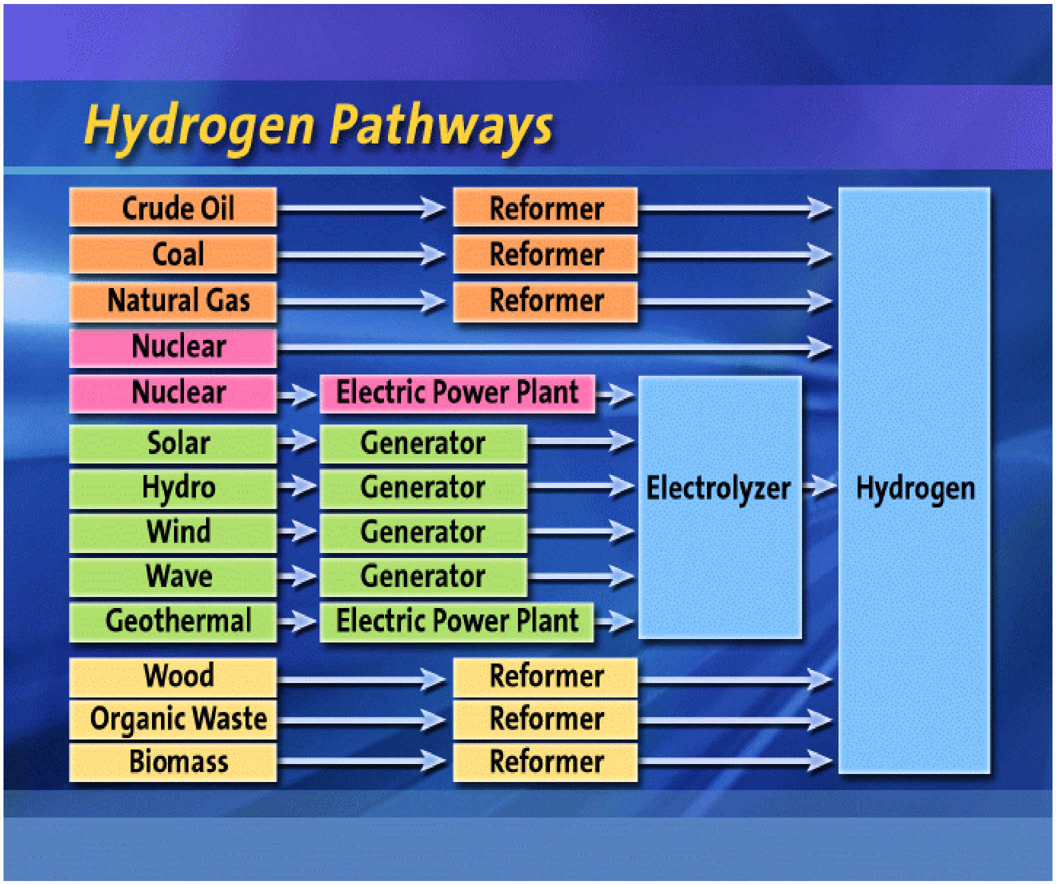
does estimate does not include the cost of converting infrastructure to deliver the fuel.

Figure 2. Hydrogen Pathways



Hydrogen can also be produced using electricity to split water (electrolysis) in an electrolyzer. If electricity is generated with nuclear, hydroelectric, wind or solar energy rather than fossil fuels, this could present a lower-emission and/or more sustainable option. However, there are environmental concerns associated with these electricity sources, especially nuclear energy. Electrolysis is also significantly more expensive than hydrocarbon reformation.[19] Chemical or thermochemical hydrolysis can also be used to produce hydrogen by splitting water, but these techniques are also more expensive than reformation.[20] However, future technological advances could potentially make these production techniques more economically attractive.

Infrastructure. If an economically viable and environmentally benign method of hydrogen production were identified, the transport, storage, and delivery of

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[18](...continued)
Outlook,"Walter Buchholtz, Exxon-Mobil. Feb. 26, 2003.

[19]Exxon-Mobil projects that hydrogen from electrolysis could be more than twice as expensive as hydrogen from natural gas (and more than four times as expensive as gasoline). Exxon-Mobil, op. cit.

[20]DOE, op. cit.

hydrogen could still make a true "hydrogen economy" prohibitively expensive and difficult to implement. Even if fuel cells were advanced significantly beyond today's technology, the United States currently lacks both the physical and regulatory infrastructure necessary to rely on hydrogen gas as a major energy carrier.

Issues for hydrogen infrastructure include: safety codes and standards, such as fire and building codes; public awareness about hydrogen fueling systems, which would be significantly different from conventional fueling systems; and training for fuel distribution and safety personnel in the physical and chemical properties of hydrogen, which differ vastly from fossil fuels. For example, hydrogen is an extremely flammable gas, but it is less dense than any other fuel, and tends to dissipate quickly in open spaces.

The required infrastructure will depend on the method and location of hydrogen production. Generation of hydrogen gas at centralized facilities would require transportation, storage and delivery of a gas or super-cooled liquid. In contrast, distributed hydrogen production, such as small-scale natural gas reformation at service stations, homes, and offices, would require a significant supply of energy (likely electricity or natural gas), as well as on-site storage facilities. The convenience and safety of the delivery would need to match that experienced by consumers today with natural gas and gasoline. Creating an extensive hydrogen infrastructure could allow for multiple feedstocks and could diversify the system in the event of changing or evolving fuel sources. Nevertheless, it is doubtful that a widespread system of hydrogen distribution will emerge quickly. More likely, transition fuels, such as natural gas and ethanol, and niche applications, such as backup power, will pave the way.

Applications: Stationary vs. Mobile. Stationary and distributed applications present the fewest challenges in infrastructure. These applications can include backup power for office buildings and power supplies for remote locations. Relative to mobile applications (e.g. transportation), storage requirements will be technically less difficult to meet and distribution will be less widespread, especially if on-site reformation is used.[21] Indeed, stationary systems are the only commercially available fuel cells today. In the future, transition niche applications including delivery trucks, taxis, and other fleet vehicles could help demonstrate the viability of hydrogen and fuel cells for mobile applications.[22]

Depending on the application, it may be more cost-effective or more compatible with existing infrastructure and codes to use conventional fuels rather than hydrogen in fuel cells. This is particularly likely in the near-term. Electricity deregulation, grid reliability issues, and the attractiveness of heat/electricity co-generation may motivate a general move to distributed power, and fuel cell technology may help satisfy the requirements of this change. In the near-term, natural gas will likely be the fuel for stationary applications, with propane a potential fuel for remote applications.

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[21]DOE, op. cit.

[22][http://www.hydrogenus.org/implementationplan.asp]

Longer-term markets, such as transportation, may make use of hydrogen gas directly in the fuel cell device, but a choice may still be required between on-board hydrogen gas generation from gasoline or alcohol fuels carried on the vehicle vs. off-board hydrogen production distributed through hydrogen fueling stations. Off-board hydrogen generation requires on-board storage of gaseous or liquid hydrogen, necessitating a unique and more demanding vehicle infrastructure and possibly limiting driving range. But the advantages of increased efficiency and simplicity could ultimately make hydrogen the more attractive choice, assuming the problems associated with infrastructure and regulation are not insurmountable.[23]

What would it mean to move to a hydrogen economy? A hydrogen economy would rely on hydrogen as the primary fuel for transportation, power, heating, and other applications. Hydrogen fuel could be used in fuel cells to generate electricity and heat in cogeneration plants. Fuel cells could replace petroleum-fueled internal combustion engines in transportation, and those same fuel cells could be used to power electrical appliances when the vehicle is not in use. Depending on how it is produced, hydrogen fuel could help improve fuel supply stability, while lowering or eliminating emissions of pollutants (e.g. nitrogen oxides, carbon monoxide, sulfur dioxide, mercury) and greenhouse gases (e.g. carbon dioxide, methane).

Major air quality benefits could be derived from the expanded use of hydrogen. For example, using hydrogen fuel generally produces only water vapor and heat as byproducts. Therefore, if the supply-related emissions from hydrogen fuel are relatively clean, overall "fuel cycle" pollutant emissions, as well as greenhouse gas emissions, could be significantly reduced. Compared to other fuels, a key advantage of hydrogen is that emissions of pollutants and greenhouse gases may be easier to control when produced from fewer centralized sources, as opposed to many mobile sources. However, there may also be the potential for higher overall emissions, depending on the primary energy source. For example, hydrogen produced from coal could lead to higher overall emissions, if the hydrogen replaced gasoline in combustion engines.

In addition to air quality improvements, there are several other potential benefits. First, because hydrogen can be produced from any primary energy source, a focus on the use of domestic resources could provide energy security gains. In a hydrogen economy, consumers could potentially purchase hydrogen like they purchase other fuels today. Suppliers would be free to select the most economical primary energy source and processing methods. However, as discussed above, there are key technical concerns with making this supply seamless to the customer, especially in delivering and storing hydrogen fuel.

Another potential benefit comes from the ability to improve the reliability of the electricity production. Because hydrogen can be produced from electrolysis, there is the potential to use existing electrical generation capacity during low-load times (such as late at night). Further, stationary and mobile fuel cells that would otherwise be idle (e.g. a fuel vehicle parked in a garage) could be used to produce electricity

[23] DOE, op. cit.

that could be used on-site or returned to the grid. However, these sorts of changes would require significant investments in electrical infrastructure.

A transition to a hydrogen economy would be expensive, requiring major investments in production facilities, supply networks, and distribution systems. In addition, consumers would need to finance the purchase of new equipment, possibly including stationary generation systems and fuel cell vehicles. However, the potential benefits in terms of air quality improvements, energy security, and greenhouse gas mitigation could be significant, especially if some key technological, economic, and policy barriers–including supply and storage issues, as well as safety concerns–are overcome.

What role can Congress play? Determining the proper role of the government in the development of a hydrogen economy has raised some key issues. Some of these issues are common to all technical and scientific research and development. Examples of these issues include whether the government should be "picking winners," and whether the government should involve itself in research that will ultimately profit corporations. On the other hand, the potential benefits to society of hydrogen and fuel cells are seen as key reasons for promoting research and development, as these benefits could lead to significant gains, such as improved air quality and greater energy security. Other key issues include whether there are other technologies such as renewable energy or hybrid vehicles that could promote the same goals more economically or with fewer technical, economic, and policy barriers.

Oversight of the Administration's Proposal. As part of the Bush Administration's National Energy Policy, the Department of Energy (DOE) has worked to identify key barriers to the development of a hydrogen economy and opportunities for increased research. Out of that effort, DOE produced two key documents, a National Hydrogen Roadmap (November 2002) and a Fuel Cell Report to Congress (February 2003) outlining necessary next steps. In January 2003, the Administration announced a major hydrogen research and development push–the President's Hydrogen Fuel Initiative. The Administration is seeking to increase funding for hydrogen and fuel cell research and development, mainly through the Department of Energy.[24] The Administration has requested a total of $1.8 billion for FY2004 through FY2008, including $720 million in new money. This initiative would transfer some funds from research on other topics, such as hybrid electric vehicles (while maintaining that research at reduced levels). The research initiative has three key components: hydrogen fuel development; fuel cell development (especially for stationary applications); and development of hydrogen-fueled automobiles.

Through the annual appropriations process, Congress will address the Administration's request for increased funding. Further, through funding

[24]The President's Hydrogen Fuel Initiative is meant to complement the FreedomCAR initiative, which coordinates research and development on fuel cell vehicles. This initiative is a cooperative research partnership between the federal government and the "Big Three" American auto manufacturers (DaimlerChrysler, Ford, and General Motors).

authorizations in comprehensive energy legislation (H.R. 6), Congress has the opportunity to support or reject the Administration's research and development plans for the next several years.

Other Congressional Actions. There are other opportunities for Congressional action to encourage or support hydrogen and fuel cell development as well. For example Congress could develop statutes and regulatory systems to simplify codes and standards for the transportation and use of hydrogen, as well as the siting of hydrogen supply facilities. Further, Congress could establish tax credits and other incentives to promote the expanded use of hydrogen fuel and fuel cell technologies. In addition, Congress could require the federal government to set an example as an "early adopter" of hydrogen fuel and fuel cell technologies.

Conclusion. There are several key barriers to the development of hydrogen fuel, fuel cells, and a hydrogen economy. These barriers include technical feasibility, economic cost, consumer acceptance, and safety. These issues will be addressed over a long-term time frame, and will evolve as research and technology expands options for hydrogen and fuel cell use. Basic understanding of the long-term potentials and limitations surrounding a hydrogen economy is critical to assessing such changes.