Hydrogen Fuel Cell Vehicles

Quick Facts

- Hydrogen fuel cell vehicles (FCVs) have a significant potential to reduce emissions from the transportation sector, because they do not emit any greenhouse gases (GHGs) during vehicle operation. Their lifecycle GHG emissions depend on how the hydrogen fuel is made.
- A future mid-size car in the 2035-2045 time frame, powered by fuel cells and using hydrogen generated from natural gas, is projected to have lifecycle GHG emissions slightly lower than that for a hybrid electric vehicle (HEV), powered by gasoline. A fuel cell vehicle would produce 200 grams of carbon dioxide-equivalent per mi (CO_2e/mi), compared to 235g CO_2e/mi for a HEV. An FCV would have near-zero lifecycle GHG emissions if the hydrogen were made, for example, from electrolysis powered by renewable electricity.
- Several major hurdles to commercial deployment must be overcome before any environmental benefits from FCVs are realized. These challenges include the production, distribution, and storage of hydrogen; fuel cell technology; and overall vehicle cost.

Background

Hydrogen FCVs are a potential option for reducing emissions from the transportation sector. Combusting fossil fuels to power conventional vehicles releases GHG emissions and other pollutants from the vehicle exhaust system (i.e., “tailpipe” emissions). In addition, there are also emissions associated with producing petroleum-based fuels (i.e., “upstream” emissions), notably emissions from oil refineries. FCVs emit no tailpipe GHGs or other pollutants during vehicle operation, and depending on how hydrogen is produced, there can be substantially lower upstream GHG emissions associated with producing hydrogen fuel.

Fuel cells are already used to generate electricity for other applications, including in spacecraft and in stationary uses, such as emergency power generators. Although the concept of a fuel cell was developed in England in the 1800s, the first workable fuels cells were not produced until much later, in the 1950s. During this time, interest in fuel cells increased, as NASA began searching for ways to generate power for space flights.[1]

Hydrogen FCVs are considered one of several possible long-term pathways for low-carbon passenger transportation (other options include vehicles powered by electricity and/or biofuels). The benefits of hydrogen-powered vehicles include the following:

- High energy efficiency of fuel cell drivetrains, which use 40 to 60 percent of the energy available from hydrogen, compared to internal combustion engines, which currently use only about 20 percent of the energy from gasoline;[2]
- Diverse methods by which hydrogen can be produced (see Box 1 below);
- Unlike all-electric vehicles (EVs), comparable vehicle range and refueling time to gasoline vehicles;
- Similar to EVs, quick starts due to high torque from the electric motor and low operating noise; and

- Lack of any GHG emissions and few other air pollutants during vehicle operation[3] and the potential for very low or no upstream GHG emissions associated with hydrogen fuel production.

Yet several key hurdles must be overcome before the introduction of FCVs on a large scale can become possible. These challenges include the production, distribution, and storage of hydrogen; fuel cell technology; and overall vehicle cost.

Description

FCVs resemble normal gasoline or diesel-powered vehicles from the outside. Similar to EVs, they use electricity to power a motor that propels the vehicle. Yet unlike EVs, which are powered by a battery, FCVs use electricity produced from on-board fuel cells to power the vehicle.

An FCV includes four major components:[4]

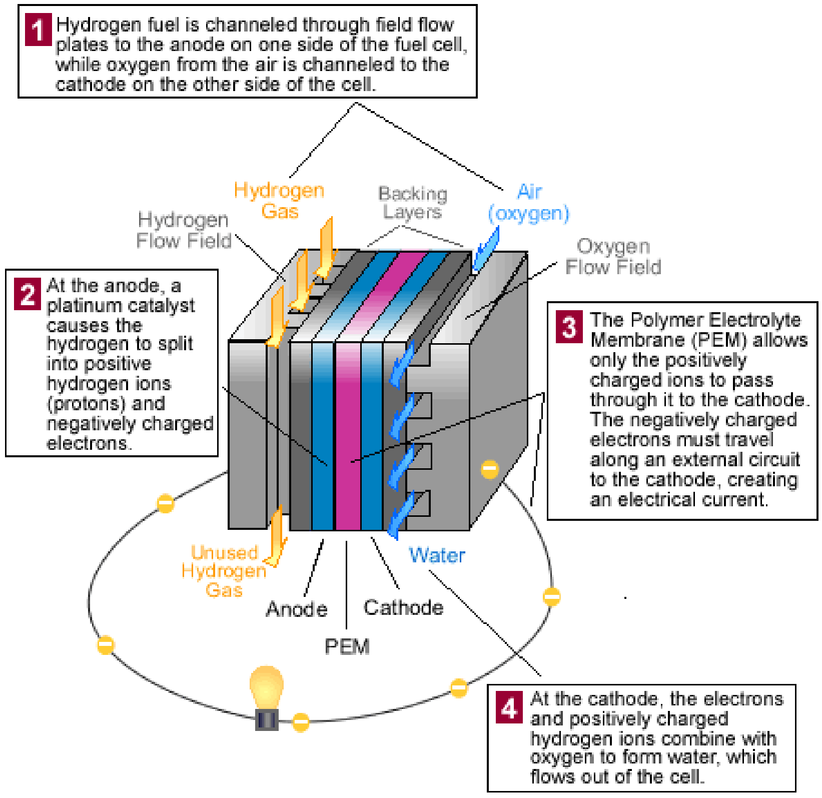
1. Fuel cell stack: The fuel cell is an electrochemical device that produces electricity using hydrogen and oxygen. In very simple terms, a fuel cell uses a catalyst to split hydrogen into protons and electrons, the electrons then travel through an external circuit (thus creating an electric current), and the hydrogen ions and electrons react with oxygen to create water.

   To obtain enough electricity to power a vehicle, individual fuel cells, like the one described below, are combined in series to make a fuel cell stack. There are several different types of fuel cells, each of which is suited for a different application. Fuel cells are typically grouped according to their operating temperature and the type of electrolyte used.[5] The amount of power generated by a fuel cell is determined by several factors including fuel cell type, size, operating temperature, and pressure at which the gases are supplied to the cell.[6] The most common type of fuel cell used in FCVs is polymer electrolyte membrane (PEM).[7]

   A fuel cell is composed of an electrolyte,[8] placed between an anode (a negative electrode) and a cathode (a positive electrode), with bipolar plates on either side. A fuel cell works as follows:[9]

   - First, the hydrogen gas flows to the anode. Here, a platinum catalyst is used to separate the hydrogen molecule into positive hydrogen ions (protons) and negatively charged electrons.[10]
   - The PEM allows only the protons to pass through to the cathode, while the electrons travel through an external circuit to the cathode. The flow of electrons through this circuit creates the electric current (or electricity) used to power the vehicle motor.
   - On the other side of the cell, oxygen gas, usually drawn from the outside air, flows to the cathode.
   - When the electrons return from the external circuit, the positively charged hydrogen ions and electrons react with oxygen in the cathode to form water, which then flows out of the cell. The cathode also uses a platinum catalyst to enable this reaction.

Figure 1: Diagram of a fuel cell.



Source: http://www.fueleconomy.gov/feg/fcv_PEM.shtml

2. **Hydrogen storage tank**: Instead of a gasoline or diesel tank, an FCV has a hydrogen storage tank. The hydrogen gas must be compressed at extremely high pressure at 5,000 to 10,000 pounds per square inch (psi) to store enough fuel to obtain adequate driving range. In comparison, compressed natural gas (CNG) vehicles use high-pressure tanks at only 3,000 to 3,600 psi.[11]

   FCVs can also be powered by a secondary fuel – e.g., methanol, ethanol, or natural gas – which is converted into hydrogen onboard the vehicle. Vehicles powered through a secondary fuel emit some air pollutants during operation due to the conversion process.[12]

3. **Electric motor and power control unit**: The power control unit governs flow of electricity in the vehicle. By drawing power from either the battery or the fuel cell stack, it delivers electric power to the motor, which then uses the electricity to propel the vehicle.

4. **Battery**: Like HEVs, FCVs also have a battery that stores electricity generated from regenerative braking,[13] increasing the overall efficiency of the vehicle.[14] The size and type of these batteries, similar to those in HEVs, will depend on the "degree of hybridization" of the vehicle, i.e., how much of the power to propel the vehicle comes from the battery and how much comes from the fuel cell stack.[15]

Environmental Benefit/Emission Reduction Potential

Because FCVs are more energy efficient than vehicles powered by gasoline and because hydrogen as a transportation fuel can have much lower lifecycle GHG emissions than fossil fuels, FCVs have the potential to dramatically reduce GHG emissions and other air pollutants from the transportation sector.

FCVs are more energy efficient than gasoline-powered vehicles. A fuel cell uses about 40 to 60 percent of the available energy in hydrogen. Internal combustion engines use only about 20 percent of the energy available in gasoline, although this is expected to improve over the long term.[16] EVs are more efficient than FCVs, using about 75 percent of available energy from the batteries.[17]

There are two models of FCVs available currently but with limited distribution, and these models' fuel economy ratings illustrate the higher efficiency of FCVs. The Honda FCX Clarity for model year 2011 has a fuel economy equivalent to 60 miles per gallon of gasoline (mpg), while the 2011 Mercedes-Benz F-Cell has a fuel economy of 53 mpg.[18] In comparison, the average fuel economy for passenger cars from model year 2010 is 33.8 mpg for a gasoline vehicle,[19] and the most efficient HEV from the same model year has a fuel economy rating of 50 mpg.[20]

In addition to being more energy efficient than gasoline-powered vehicles, FCVs can also have much lower lifecycle GHG emissions compared to vehicles fueled by petroleum-based fuels. FCVs emit only heat and water during operation (i.e., no tailpipe GHGs). Lifecycle GHG emissions from FCVs thus depend, mainly, on the process used to produce hydrogen. Hydrogen can be produced from fossil fuels (coal and natural gas), nuclear, renewable energy technologies (wind, solar, geothermal, biomass), and hydroelectric power (see Box 1 for more information).

Lifecycle GHG emissions for an FCV are the sum of emissions from the production and distribution of hydrogen, the production of the vehicle, and vehicle operation. Estimates made for the U.S. Department of Energy (DOE) project that a future mid-size FCV (in the years 2035 to 2045), powered by hydrogen from natural gas, will have lifecycle GHG emissions slightly lower than that for an HEV, powered by gasoline (200g CO_2e/mi compared to 235g CO_2e/mi).[21] Another study, from the Massachusetts Institute of Technology (MIT), found similar results: lifecycle emission from an FCV, using hydrogen produced from natural gas, would be comparable to those from a hybrid vehicle.[22]

With hydrogen produced using less carbon-intensive methods – coal gasification with CCS, biomass gasification, or electrolysis powered by nuclear power or renewable – lifecycle GHG emissions would drop significantly. With biomass gasification or electrolysis, lifecycle emissions for an FCV are lower than all other vehicle types, with the exception of EVs recharged using electricity from renewable sources.

Over the long term, the reduction of overall transportation sector emissions attributable to FCVs will depend on the total number of vehicles in use. A 2008 study by the National Academy of Sciences (NAS) provides one measure of the potential for GHG emission reductions from FCVs. The NAS study estimated the maximum practicable penetration rate for FCVs in the United States in the 2008 to 2050 time frame. The study projected that FCVs could account for approximately 2 million vehicles, out of a total of 280 million light duty vehicles, in 2020, and grow rapidly from then on, increasing to 25 million vehicles in 2030.

Box 1: Hydrogen Production Pathways

Natural gas: Nearly all of the hydrogen used in the United States (95 percent) is produced through a process called steam methane reforming. This process breaks down methane (CH4), a hydrocarbon, into hydrogen and carbon dioxide (CO2). The methane in natural gas is reacted with water (in the form of high-temperature steam) to produce carbon monoxide and hydrogen. These gases are reacted with water again, in a process called a water shift reaction, to produce more hydrogen and CO2.

Gasification: Gasification processes include a series of chemical reactions in which coal or biomass is "gasified" (i.e., converted into gaseous components) using heat and steam. A series of chemical reactions is then used to produce a synthesis gas (a gas mixture that contains varying amounts of carbon monoxide and hydrogen), which is reacted with steam to produce more hydrogen. Producing hydrogen via coal gasification is significantly more efficient than burning coal to produce electricity that is then used in electrolysis.

Although gasification technology is commercially available, the challenge is lowering the amount of CO2 emitted from the process to decrease upstream emissions from the use of FCVs. Coal gasification with carbon capture and sequestration (CCS) or biomass gasification can produce hydrogen with very low or no net GHG emissions, although both these technologies are only in the early stages of commercial-scale deployment. (See Climate Techbook: Carbon Capture and Storage http://www.pewclimate.org/technology/factsheet/ccs.)

Electrolysis: In electrolysis, an electric current is used to split water into hydrogen and oxygen. Electrolysis is in advanced stages of technological development and could play an important role in the near to mid term. Net GHG emissions from electrolysis for hydrogen production depend on the source of the electricity used. If powered by electricity from low-carbon sources (i.e., renewable technologies, nuclear, power, or fossil fuels coupled with CCS), the process generates little to no GHG emissions.

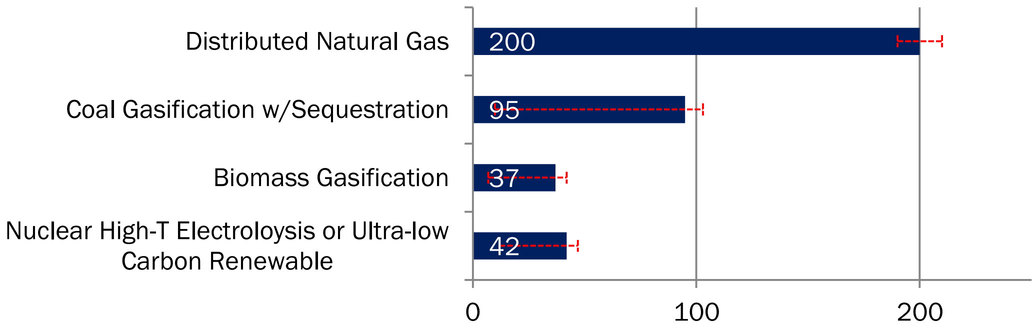
With nuclear high-temperature electrolysis, the efficiency of the process increases. In this type of electrolysis, the heat from the nuclear reactor is used to increase the water temperature and thereby reduce the amount of electricity needed for electrolysis.

High-Temperature Thermochemical Water-Splitting: This is another water-splitting method that uses high temperatures from nuclear reactors or from solar concentrators (lenses that focus and intensity sunlight) to generate a series of chemical reactions that split water, producing hydrogen. The process is in the early stages of development but considered a potential long-term technology, since it is powered by non-GHG emitting technologies and yields a very low-carbon hydrogen fuel.

Photobiological and Photoelectrochemical Processes: These processes use energy from sunlight to produce hydrogen, although both are currently in early stages of research. Photobiological processes use microbes, such as green algae and cyanobacteria. When these microbes consume water in the presence of sunlight, hydrogen is produced as a byproduct of their metabolic processes. Using special semiconductors and sunlight, photoelectrochemical systems produce hydrogen from water as well.

From U.S. DOE, Office of EERE, Fuel Cell Technologies Program. "Hydrogen Production." http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_production.pdf, November 2008; and Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008.

Figure 2: Well-to-Wheels GHG Emissions for Future FCV based on different hydrogen production processes in gCO2e/mi.



Source: http://www.hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

With these levels of market penetration, the study estimated that gasoline use would decrease by 24 percent in 2035 and by nearly 70 percent in 2050, compared to business-as-usual (BAU) levels. GHG emissions for light-duty vehicles would decline by 20 percent in 2035 and by more than 60 percent in 2050, as compared to BAU levels.[23] In this scenario, hydrogen is initially produced from natural gas, then from a mixture of sources – natural gas, biomass gasification, and coal gasification with CCS. These estimates assumed that all technical goals were met, consumers accepted FCV technology, and the appropriate policies were implemented for the market transition period.

There are multiple options for reducing GHG emissions from transportation over the long-term. The actual role that FCVs will play will depend on the relative costs of FCV and other low-carbon transportation options and measures adopted by policymakers to reduce GHG emissions.

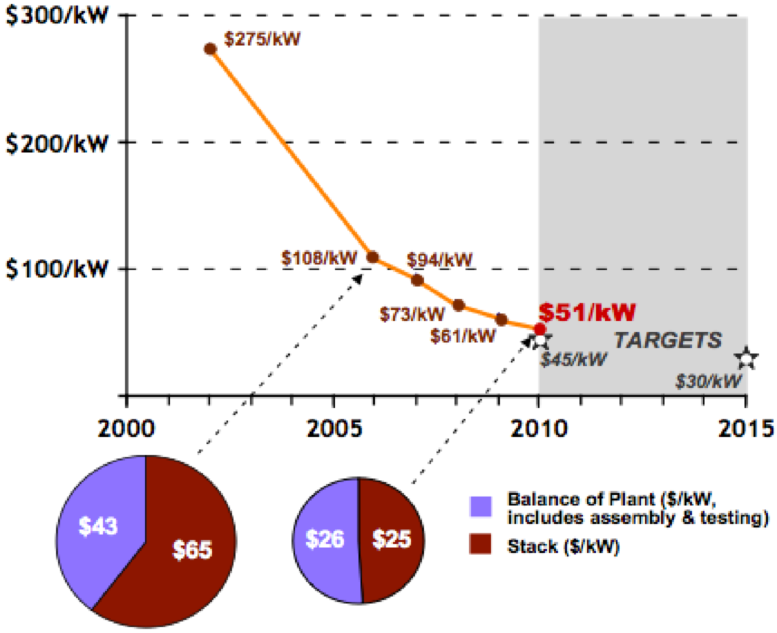
Cost

Although the cost of fuel cells have decreased significantly, the cost for a fuel cell system is almost double that of an internal combustion engine. [24]

A study by Directed Technologies, Inc. for the DOE estimated the lowest production costs for an FCV with an 80 kilowatt (kW) system with production levels of 500,000 systems a year. The study found that current costs for a fuel cell system (in 2010) are approximately $51/kW, close to the DOE target of $45/kW. For 2015, the study projected that costs would decrease to $39/kW by 2015. The DOE goal for that year is $30/kW.[25]

In addition to system costs, the costs of hydrogen storage are still much higher than the target set for commercialization, which is $2 per kilowatt-hour (kWh). Currently, onboard storage costs are $15-18/kWh, depending on the level of storage pressure.[26]

Figure 3: Reduction in Fuel Cell System Cost, 2002 to 2010 (in 2002$).



Source: http://www.hydrogen.energy.gov/pdfs/10004_fuel_cell_cost.pdf

Overall vehicle costs are also substantially higher than that for conventional vehicles. Toyota has announced plans to sell an FCV in 2015 for $50,000, approximately two times that for a comparable conventional vehicle.[27] In a 2008 study, the NAS estimated the average cost of an FCV from 2008 to 2023 at $39,000 per vehicle, including research, development, and deployment (RD&D) costs.[28] A study by MIT that examined energy and environmental impacts of fuel and vehicle technologies for light-duty vehicles indicated the costs would decrease over the long-term. The study estimates that a fuel cell car in 2035 will cost $5,300 more than its gasoline counterpart, which would have a retail price of $21,600 (in 2007$).[29]

Current Status

Some believe that FCVs are the most promising long-term solution to the challenge of low carbon transportation. Until recently, FCVs were one of the DOE's main areas of focus for long-term research. In 2010, DOE's proposed budget reduced funds for RD&D significantly to focus on nearer-term options for GHG reductions, such as plug-in electric vehicles (PEVs).[30]

FCVs are not yet commercially available, but manufacturers are producing small fleets of demonstration vehicles. Both Honda and Mercedes have FCVs available for lease currently but with limited distribution only in Southern California.[31] Significant penetration of FCVs will require a substantial development of hydrogen refueling infrastructure, as well as improvements in performance and reductions in costs.[32] Studies by the NAS and MIT project that FCVs will be available commercially by 2020, but only if technological and cost issues are resolved.[33]

The development of any new technology often exhibits a "chicken-and-egg" problem – vehicle manufacturers are unwilling to produce vehicles unless there is a guaranteed supply of hydrogen, while hydrogen producers will not supply fuel unless there is a demand for it. Currently, there is no nationwide hydrogen distribution infrastructure, which limits the use of FCVs to areas where filling stations do exist.

Box 2: Hydrogen Distribution

Currently, there is no infrastructure for distributing hydrogen, like that for fossil fuels. Because hydrogen has less energy per unit volume, distribution costs are higher than those for gasoline or diesel. Most hydrogen is produced either on-site or near where it is used, usually at large industrial sites. It is then distributed by pipeline, high-pressure tube trailers, or liquefied hydrogen tankers. Pipeline is the least expensive way to distribute hydrogen; the last two, while more expensive, can be transported using different modes of transportation – truck, railcar, ship, or barge.

Building network of pipelines and filling stations for FCVs would require high initial capital costs. One potential solution is to produce hydrogen regionally or locally to limit issues with distribution. A second is to use a phased approach. At first, hydrogen distribution (and sales of FCVs) could be concentrated in a few key areas. The next phase would expand the distribution sales network by targeting geographic corridors (e.g., New York-Boston-Washington, D.C.) and then gradually expand to other regions. This phased approach would remove the need for stations all across the United States at the outset, and allow for a slower and affordable build-up in the number of stations and areas served over time.

From U.S. DOE, Office of EERE, Fuel Cell Technologies Program. "Hydrogen Distribution and Delivery Infrastructure." http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_delivery.pdf November 2008; and Green, D., et al. "Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements."

Obstacles to Further Development/Deployment

Fuel cell technology: Significant improvements in fuel cell durability and costs are needed for FCVs to achieve commercial success. These are limited by the properties of catalysts and available membrane materials. Targets set by industry aim for an operating life of 5,000-5,500 hours and 17,000 start/stop cycles for a fuel cell system. Achieving this target would allow FCVs to be competitive with conventional vehicles in terms of durability. To date, automotive fuel cells have not demonstrated this level of reliability.[34]

On-board hydrogen storage: Although hydrogen contains three times more energy per weight than gasoline, it contains one-third of the energy per volume. Storing enough hydrogen to obtain a vehicle range of 300 miles would require a very large tank, too large for a typical car.[35] Currently the most cost-effective option is using high-pressure tanks, yet these systems are large, heavy, and too costly to make FCVs cost-competitive.[36] Other options include storing hydrogen in metal- or chemical-hydrides[37] or producing hydrogen onboard.

Hydrogen production: Hydrogen can be produced using a variety of methods, with substantially different GHG footprints (see Box 1 above). For FCVs to be competitive as a GHG-reduction strategy, more development of low-cost and low-GHG hydrogen production methods will be needed.

Distribution infrastructure: There is currently no national system to deliver hydrogen from production facilities to filling stations, similar to that for diesel or gasoline. A completely new distribution infrastructure will be required to allow mass market penetration of FCVs (see Box 2 above).

Vehicle cost: For FCVs to become cost-competitive, high production volumes are needed to make vehicle plus fuel costs less than those for a gasoline vehicle.

Competition with other technologies: There is a range of potential alternative technologies available for use in the transportation sector, including higher efficiency gasoline- and diesel-powered vehicles, biofuels, HEVs, and PEVs. To be competitive with these technologies, FCVs will have to improve in terms of performance, durability, and cost. [38]

Safety and public acceptance: Safety concerns include the pressurized storage of hydrogen on-board vehicles. Hydrogen gas is odorless, colorless, and tasteless, and thus unable to be detected by human senses. Unlike natural gas, hydrogen cannot be odorized to aid human detection; furthermore, current odorants contaminate fuel cells and impair cell functioning. It is also more combustible than gasoline, although flames produce lower radiant heat which limits the chance of secondary fires.[39] Improved on-board storage will reduce safety concerns.

Consumers will have to become familiar with and embrace fuel cell technology before FCVs can become widespread.[40] In addition, the durability and reliability of fuel cells will need to be comparable to the lifetime of a conventional passenger vehicle, approximately 14 years.

Policy Options to Help Promote FCVs

Substantial policy support and investment is required for FCVs to achieve market readiness. Policies should initially focus on RD&D and then transition to policies to aid market penetration once key challenges are overcome.

- Government support through research, development, and deployment initiatives and grants: Government support will need to deal with the “chicken-and-egg” problem by supporting both the development of FCV technology to bring it to market readiness, e.g., by helping manufacturers produce demonstration vehicles, and also build out of the infrastructure for hydrogen distribution. To achieve substantial market penetration of FCVs, the NAS estimates that the government support required will be approximately $55 billion from 2008 to 2023, with an investment from private industry of $145 billion over the same period.[41]
- Tax and/or subsidy policies to reduce the high initial cost of FCVs compared to conventional vehicles: Government tax and/or subsidy policies are needed to reduce the high initial cost of FCVs, in order to make them more cost-competitive with gasoline vehicles. These policies can be directed at either producers – manufacturers of FCVs and suppliers of hydrogen – to reduce

production and distribution costs, or consumers who purchase FCVs. There is currently a tax credit of $0.50/gallon for hydrogen sold for use in a motor vehicle, which expires in September 2014.[42]

- GHG reduction policies: These policies can focus on reducing sectoral and/or economy-wide GHG emissions. For example, a sectoral performance standard (e.g., a low-carbon fuel standard, or LCFS) would set targets for reductions in GHG intensity for the entire transportation fuel supply and provide a level playing field for all transportation energy sources that may be used in the future, including biofuels, electricity, or hydrogen. Economy-wide policies that reduce oil use and GHGs can include GHG cap-and-trade systems and other policies that put a price on GHG emissions. These policies can encourage a broad array of cost-effective options for reducing GHG emissions across economic sectors. A reduction in economy-wide GHG emissions would ensure that hydrogen production generates less CO_2 emissions (see Box 1 for hydrogen production pathways), reducing upstream emissions from the use of FCVs.

Related Business Environmental Leadership Council (BELC) Company Activities

Air Products

Daimler

GE

IBM

Johnson Controls

Toyota

United Technologies

Related Pew Center Resources

Greene, D. L., & Plotkin, S. (2011). *Reducing Greenhouse Gas Emissions From U.S. Transportation*. Arlington: Pew Center on Global Climate Change.

Further Reading / Additional Resources

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. Fuel Cell Technologies Program: Informational Resources (http://www1.eere.energy.gov/hydrogenandfuelcells/pubs_educational.html)

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. Alternative and Advanced Fuels: Hydrogen. http://www.afdc.energy.gov/afdc/fuels/hydrogen.html

Bandivadekar, Anup, et al. "On the Road in 2035: Reducing Transportation's Petroleum Consumption and

GHG Emissions." http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/ Massachusetts Institute of Technology, July 2008.

Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008. http://www.nap.edu/catalog.php?record_id=12222

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1 US DOD, Fuel Cell Test and Evaluation Center. "History." http://www.fctec.com/fctec_history.asp. Accessed 31 December 2010.

2 U.S. DOE, Office of EERE, Fuel Cell Technologies Program. "Hydrogen Fuel Cells." http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_fuelcell_factsheet.pdf, November 2008.

3 As with conventional vehicles, FCVs may emit GHGs directly from air conditioning systems (a "direct" source of emissions). The refrigerant used in air conditioning systems is a pressurized gas (HFC-134a, a greenhouse gas), which can leak from small openings or cracks in the system.

4 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles." http://www.fueleconomy.gov/feg/fuelcell.shtml, 20 December 2010. Accessed 1 January 2011.

5 The electrolyte is an ion conducting material that allows only the appropriate ions to pass between the anode and cathode. The type of electrolyte plays an important role in regulating the chemical reaction. If other substances or free electrons travel through the electrolyte, this could disrupt the chemical reaction.

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8 In a fuel cell, the electrolyte is a non-metallic conductor of electrical ions in a solid membrane. NREL. "Fuel Cells." http://www.nrel.gov/learning/eds_hydro_fuel_cells.html, 2 December 2009. Accessed 1 January 2011.

9 For an animation of the process, visit http://www.fueleconomy.gov/feg/animation/swfs/fuelcellframe.html.

10 U.S. DOE, Office of EERE, fueleconomy.gov. "How Fuel Cells Work." http://www.fueleconomy.gov/feg/fcv_PEM.shtml, 20 December 2010. Accessed 1 January 2011.

11 Natural Gas Vehicles for America. "Technology." http://www.ngvc.org/tech_data/index.html. Accessed 1 January 2011.

12 U.S. DOE, Office of EERE, Alternative & Advanced Vehicles. "What is a fuel cell vehicle." http://www.afdc.energy.gov/afdc/vehicles/fuel_cell_what_is.html, 31 August 2010. Accessed 17 December 2008.

13 Regenerative braking slows a vehicle by converting its kinetic energy into stored energy in a battery, which can later be used to power the electric motor.

14 U.S. DOE, Office of EERE, Alternative & Advanced Vehicles. "What is a fuel cell vehicle." http://www.afdc.energy.gov/afdc/vehicles/fuel_cell_what_is.html, 31 August 2010. Accessed 17 December 2008.

15 See the following for more on hybridization of FCVs: Pesaran, Ahmad. "Fuel Cell/Battery Hybrids: An Overview of Energy Storage Hybridization in Fuel Cell Vehicles." Presented at 9th Ulm Electrochemical Talks, Ulm, Germany, May 17-18, 2004.

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17 U.S. DOE, Office of EERE, fueleconomy.gov. "Electric Vehicles." http://www.fueleconomy.gov/feg/evtech.shtml, 20 December 2010. Accessed 1 January 2011.

18 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Fuel Economy" http://www.fueleconomy.gov/feg/fcv_sbs.shtml 16 December 2010. Accessed 17 December 2010.

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20 Toyota Prius. U.S. DOE, Office of EERE, fueleconomy.gov. "2010 Fuel Economy Guide." http://www.fueleconomy.gov/feg/FEG2010.pdf. Accessed 7 February 2011.

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23 The study used the 2008 EIA high-oil-price scenario, which was extended to 2050 by the committee, as the reference/BAU case for the analyses. Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008.

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26 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Challenges." http://www.fueleconomy.gov/feg/fcv_challenges.shtml 16 December 2010. Accessed 17 December 2010.

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30 LaMonica, M. "DOE to slash fuel cell vehicle research." 8 May 2009, http://news.cnet.com/8301-11128_3-10236740-54.html#ixzz1Cq42Itga. Accessed on 2 February 2011.

31 In addition, General Motors, Hyundai, Kia, Nissan, Toyota, and Volkswagen are also in the process of testing FCV prototypes. For more information, visit http://www.fuelcellpartnership.org/progress/vehicles.

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