Environmental and Energy Study Institute

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Fact Sheet

Fuel Cells

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Imagine a device that could take the most abundant element in the universe and convert it into electricity, heat, and water, without emitting any harmful pollution. Sounds too good to be true? But, such a device exists—the fuel cell.

A fuel cell is, in a way, a battery that can be refueled (as opposed to recharged). Fuel cells generate electricity by combining oxygen and hydrogen (or a hydrogen-rich fuel source) in a chemical reaction, and continue to operate so long as fuel is provided. When pure hydrogen is used, the only byproduct is heat and water—there are no harmful emissions at all.

Hydrogen does not exist in its natural state on Earth, and so must be generated from other sources, such as natural gas/biogas (through reformation) or by electrolyzing water (each molecule of water contains two hydrogen atoms). Electrolyzing water is, in effect, a reversal of the process that enables fuel cells to generate electricity. Electrolysis can be powered by clean, renewable energy sources like geothermal, solar, water or wind. In such a manner, the production of hydrogen and its use in a fuel cell can be completely pollution-free.

Fuel cells can also be designed to run on other fuels, provided they contain hydrogen (such fuels include *hydro*carbons—such as natural gas and methane—or alcohols like ethanol and methanol). In this case, the hydrogen needed to power the cell is extracted from the fuel, using a reformer, or in some cases the fuel cell directly reforms the fuel itself. When using fuels other than pure hydrogen, a fuel cell emits some carbon pollution as well as trace amounts of other pollutants, but substantially less than a combustion-based engine. Fuel cell systems are also more efficient than their combustion-based counterparts, even after taking into account energy losses resulting from their support systems (e.g., gas compressors or fuel reformers). A fuel cell's efficiency advantage is even more pronounced when the heat fuel cells produce is recovered in a combined heat and power (CHP) system, which allows for overall energy efficiencies of up to 90 percent.

In addition to being able to run on several types of fuels, fuel cell technology can also operate at many different scales, from small devices powering smartphones, all the way up to megawatt-scale power plants that can power tens of thousands of homes (with mid-sized devices powering vehicles, forklifts, homes, and everything in between).

This fact sheet will give an overview of fuel cells, examining their strengths and challenges, applications, and the impact of federal and state clean energy policies on their commercialization and deployment in the marketplace.

FUEL CELL STRENGTHS & CHALLENGES

There are many different types of fuel cells, based on the catalyst used. Types of fuel cells include: Polymer Electrolyte Membrane (PEM), Direct Methanol, Alkaline, Phosphoric Acid, Molten Carbonate, Solid Oxide, and Microbial, among others. Each has its own strengths and challenges, and some are better suited for certain applications. In general, however, fuel cells have the following key strengths and challenges compared to internal combustion engines and batteries, their two most comparable rivals.

Fuel Cell Strengths

General Strengths

- ***Reliability and very quiet operation.*** Fuel cells have no moving parts, which makes them potentially much more reliable than combustion engines and wind turbines (and significantly quieter in operation). Stationary fuel cells, in particular, need very little maintenance (with servicing required once every one to three years).
- ***Scalability.*** Fuel cells are modular in construction, and offer consistent performance regardless of their size.
- ***Small footprint.*** A fuel cell takes up considerably less space than a comparably-scaled wind or solar system, and can be sited both outdoors and indoors.

Versus internal combustion engines (for vehicles)

- ***Pollution-free.*** Fuel cells do not emit any pollution at their point of use when run on pure hydrogen. The "well-to-wheels" emissions of fuel cell electric vehicles running on renewable hydrogen (extracted from water using clean energy) are almost 100 percent lower than those of conventional gasoline vehicles.
- ***Low emissions.*** When running on hydrogen extracted from natural gas (the most common source at present), fuel cells still emit about 50 percent fewer greenhouse gas emissions than combustion engines.
- ***High efficiency.*** Fuel cells are more efficient than combustion engines as they operate at a higher thermodynamic efficiency. Combustion engines must first convert their fuel into heat, then into mechanical energy, and finally into electricity. Fuel cells skip those intermediary steps.

Versus batteries (for vehicles and stationary applications)

- ***Ongoing Power / Fast Refueling.*** Fuel cells can be refueled, which is substantially faster than recharging. Fuel cell vehicles, for instance, can be refueled in 3-5 minutes (just like refueling a gasoline vehicle). Stationary fuel cells can be plugged directly into a fuel source, and so provide resilient power without interruption. Moreover, batteries can only be recharged a limited number of times before they need to be completely replaced—and they contain hazardous materials, making it expensive to dispose of them properly.
- ***Higher Energy Density.*** A fuel cell gives more bang per energy buck than a similarly-sized battery. A fuel cell-equipped electric car could power a typical U.S. household for two days, something a battery would struggle to do. A fuel cell-powered smartphone could be left on standby for one week, rather than 1-2 days for a lithium battery-powered phone.
- ***Lighter.*** In general, fuel cell systems are lighter than comparable battery systems, even taking into account the support systems required to store hydrogen.

Fuel Cell Challenges

A proven, highly flexible technology that runs on the most abundant element in the universe and can be emissions-free… Why haven't fuel cells overrun the world? Fuel cells have been around since 1839, when the first one was built by Sir William Grove—just 39 years after the invention of the battery by Alessandro Volto. But it was only in the 1960s, when NASA developed fuel cells for its space program, that fuel cell research and development really began in earnest. The first demonstrations for cars and stationary applications took place in the 1990s and 2000s, making fuel cells a relatively young technology. To put things in perspective, the photovoltaic effect, which makes solar panels possible, was also discovered in 1839, but solar photovoltaic power has only really taken off in the past five years.

So far, fuel cells have thrived in certain niche applications, such as space (satellites, the space station…), forklifts in warehouses, telecom backup power, and primary and backup power for critical facilities (including credit card processing and data centers).

The three main obstacles to the spread of fuel cells have been their price, the cost of producing hydrogen, and the difficulty of storing hydrogen. Another challenge is the need for pure fuels.

- ***Cost.*** Cost has long been the main obstacle to the widespread commercialization of fuel cells. Most PEM fuel cells need platinum, an expensive and rare metal. However, the quantity of platinum they require has fallen dramatically, and ongoing R&D efforts are seeking to further reduce the amount required, or eliminate it entirely. Other types of fuel cells do not require platinum or other expensive catalysts.

- ***Producing Hydrogen.*** Hydrogen is by far the most abundant element in the universe, accounting for almost 75 percent of normal matter. Unfortunately, hydrogen does not exist in its natural, pure state on Earth. It must be derived from compounds such as water (H_2O) or hydrocarbons. This process is energy-intensive, but can be powered by renewable energy sources. When hydrogen is extracted from hydrocarbons, which is currently the cheapest method (via methane reformation), the process emits harmful pollution and greenhouse gases, but less than would be emitted by burning the hydrocarbon. The United States currently produces about 3 billion cubic feet of hydrogen *per day* (about 9 million metric tons a year), enough to power 36-41 million fuel cell electric vehicles.

- ***Storing Hydrogen***. Hydrogen is difficult to store. It is the lightest element, meaning it must be heavily compressed in order to fit into a practical container. Storing hydrogen as a gas requires high-pressure fiber-composite tanks. Storing it as a liquid requires keeping its temperature down to cryogenic levels. Another alternative is to store it as a component of a hydrocarbon or alcohol, releasing it with an onboard reformer. This extraction emits some pollution, but substantially less than a combustion-based engine.

- ***Fuel Purity.*** Fuel cells need to run on a relatively pure fuel, free of contaminants. Combustion engines are more tolerant, and batteries do not use an external fuel at all.

Two other major challenges are social and economic in nature (rather than technical):

- ***Lack of Fueling Infrastructure (for fuel cell electric vehicles).*** What comes first, the vehicle or the fueling station? This chicken-or-egg conundrum is a problem: retailers don't want to invest in hydrogen fueling stations without a critical mass of fuel cell electric vehicles (FCEVs) on the road, but such a critical mass is hard to reach without a widespread network of stations. In addition, hydrogen is competing with an already-existing, entrenched gasoline infrastructure representing substantial sunk costs for the transportation sector.

  Fortunately, the chicken-or-egg issue can be tackled—today's extensive network of gasoline stations didn't just appear overnight after all, nor did electric vehicle charging stations. As fuel cell electric vehicles enter the marketplace (the first mass-produced one, Hyundai's Tucson Fuel Cell, hit U.S. roads in June 2014, and the first Toyota Mirai FCEVs were sold in the United States in October 2015), authorities and automakers are taking steps to ensure that a hydrogen fueling infrastructure will be ready for them. California, with strong support from Honda and Toyota, is leading the way, with almost 50 hydrogen stations planned by the end of 2016, up from eight today. Toyota and Air Liquide are working to establish a hydrogen infrastructure in the Northeast, and the H2USA partnership is working to develop one on a national scale.

- ***Fear of Hydrogen.*** For many, the first thing that comes to mind when hydrogen is mentioned is either the Hindenburg disaster or hydrogen bombs. Yet hydrogen is much less threatening than it is made out to be. A colorless and odorless gas, it is non-toxic and safe to breathe. Hydrogen, like all fuels, is flammable, but it is safer than gasoline, as it dissipates quickly when accidentally released (being lighter than air). In the United States, hydrogen is routinely piped through 700 miles of pipelines without incident, and trucks safely transport over 70 million gallons of liquid hydrogen every year. Hydrogen has been produced, stored, and delivered safely in the United States for more than 50 years. Overcoming the stigma attached to hydrogen should not be insurmountable.

APPLICATIONS

Fuel cells can be used in a variety of applications, which can be categorized into three groups:

1) **Portable power generation.** Compact, portable fuel cell systems can be used to recharge batteries or directly power consumer electronics (such as laptops and smartphones). Portable fuel cells can also supply off-the-grid backup power (in remote locations, for instance) or on-the-go power.

2) **Stationary power generation.** Stationary fuel cells can be an important part of distributed generation, and are often used as primary or backup power for large energy infrastructures. They are highly efficient: 50 percent for electricity generation, and more than 90 percent with heat recovery (plus there is no need for long transmission lines, with their associated power loss). There are three main uses for stationary fuel cells: combined heat and power (CHP), uninterruptible power supplies (UPS), and primary power units.

    a. **CHP systems** range from 0.5 kilowatt (kW) to several megawatts (MW), and use both the heat and electricity generated by the fuel cell to maximize fuel efficiency (the heat, which is lost in other systems, can be used to heat water and/or provide space heating for a building, for instance). A fuel cell CHP system runs with 80-95 percent efficiency. More than 120,000 fuel cell CHP units have been installed in Japanese homes. In the United States, CHP fuel cells have been installed in grocery stores, hospitals, corporate facilities, and other sites ranging from 200 kW to more than 1 MW.

    b. **UPS systems** are sources of uninterrupted power, and are primarily used as backup power during grid outages. They can replace diesel-powered emergency generators in critical facilities like hospitals and server farms. Cellphone towers equipped with fuel cells were able to keep running during Hurricane Sandy, keeping vital communication links open.

    c. **Primary power units** are large stationary units that can be used to generate power for facilities or for the grid. Companies such as Apple, eBay, Macy's, and Verizon use fuel cells as primary power units. A 14.9-MW Dominion fuel cell facility—the largest in the United States—was put into service in December 2013. A 59-MW facility near Seoul in South Korea is the world's largest.

3) **Power for transportation.** Fuel cells can be used to power scooters, forklift trucks, buses, trains, boats, aircraft, and cars. Fuel cell-powered forklifts have been especially popular, with customers including BMW, Coca-Cola, FedEx, Walmart, and Whole Foods. Fuel cell cars from Hyundai, Toyota, and Honda have hit or about to hit the U.S. market (Hyundai was the first to market in June 2014). Several other automakers are engaged in fuel cell electric vehicle R&D partnerships. The National Renewable Energy Laboratory is evaluating fuel cell electric bus programs throughout the nation. These buses are nearing the durability and operating cost targets required for widespread commercialization.

A GROWING INDUSTRY

The global fuel cell market is forecast to reach $3 billion in sales by 2020, up from $1.3 billion in 2013, the first time sales surpassed the $1 billion mark. Those projections may be too conservative, however, as revenue in 2014 reached $2.2 billion, almost doubling the previous year's total. This represents a major opportunity for U.S. manufacturers, as more than 140 MW of the 180 MW worth of fuel cells installed in 2014 shipped from North America.

The rise of stationary fuel cells for power generation is primarily responsible for the industry's projected growth. Korea and the United States have the largest share of large stationary fuel cell systems, and Japan has the most residential fuel cells. Market growth is pronounced in Europe, which has been making strong efforts to curb its carbon emissions.

Every year, the U.S. Department of Energy releases two reports on the fuel cell industry that provide detailed information and showcase the industry's status and strong growth prospects: *The Business Case for Fuel Cells* and *State of the States: Fuel Cells in America.*

FEDERAL AND STATE POLICY DRIVERS

Countries with policies that promote clean energy are the most likely to have growing fuel cell markets.

Federal Policy

In the United States, several Department of Energy (DOE) initiatives support the development of fuel cell technologies, with a goal of making them cost competitive. The DOE's Fuel Cell Technologies Office, with an enacted FY2015 budget of $97 million, and a 2016 budget request of $103 million, supports hundreds of RD&D projects with fuel cell companies, universities, national laboratories and other stakeholders around the United States. It also facilitates private-public partnerships, as well as international cooperation.

The Fuel Cell Technologies Office has two main goals for 2020: (1) bring the cost of automotive fuel cell systems down to $40 per kilowatt, and ultimately down to $30 per kilowatt (which would be competitive with gasoline-powered light-duty vehicles); and (2) bring the cost of renewable hydrogen fuel (extracted from water or biogas) to less than $4 per gallon gasoline equivalent.

The trend lines are promising: DOE initiatives have reduced the cost of automotive fuel cell systems to $55 per kilowatt in 2014 (assuming high volume manufacturing), 30 percent less than in 2008 and 50 percent less than in 2006; reduced the quantity of platinum necessary in PEM fuel cells by more than doubling its efficiency as a catalyst (to 6.3 kilowatts per gram of platinum in 2014, up from 2.8 kilowatts per gram in 2008); and reduced the cost of electrolyzer stacks (to extract hydrogen from water) by 80 percent since 2002. According to the Fuel Cell Technologies Office, a sampling of its projects showed that they resulted in revenues four times larger than initial DOE funding.

Fuel Cell Technologies Office (Department of Energy) Budget

	FY 2014 (Enacted)	FY 2015 (Enacted)	FY 2016 (Requested)
Fuel Cell R&D	$33 million	$33 million	$36 million
Hydrogen Fuel R&D	$37 million	$35 million	$41 million
Manufacturing R&D	$3 million	$3 million	$4 million
Systems Analysis	$3 million	$3 million	$3 million
Technology Validation	$6 million	$11 million	$7 million
Safety, Codes and Standards	$7 million	$7 million	$7 million
Market Transformation	$3 million	$3 million	$3 million
NREL User Facility	$1 million	$2 million	$2 million
TOTAL for fuel cell technologies	**$93 million**	**$97 million**	**$103 million**

Source: Department of Energy (numbers have been rounded)

The Fuel Cell Technologies Office's Market Transformation program is premised on the idea that markets can be both efficient and environmentally friendly with the help of federal regulation. The program's goal is “to accelerate the expansion of hydrogen and fuel cell use by lowering the lifecycle costs of hydrogen and fuel cell technologies and identifying and reducing the barriers impeding full technology commercialization.” The program demonstrates the value of fuel cells in markets and develops models for real-world applications to further fuel cell development in the economy.

The *American Recovery and Reinvestment Act* (ARRA) of 2009 provided an additional federal impetus for fuel cell development. ARRA allocated $96 million in DOE recovery funds to deploy fuel cell systems to create jobs, cut emissions, and diversify America’s energy portfolio.

The federal government also incentivizes fuel cell purchases through various tax credits. The two currently applicable to fuel cells are the Residential Renewable Energy Tax Credit, and the Business Energy Investment Tax Credit. The previously available Fuel Cell Motor Vehicle Tax Credit and Hydrogen Fuel Infrastructure Tax Credit have expired.

State Policy

Many states have policies that specifically promote fuel cells and hydrogen, and many more have policies that promote clean energy and apply to fuel cells. Such policies vary widely from state-to-state, but they mainly fall under one of four categories:

1) **Net metering** can be used as a tool to incentivize fuel cell use. It "allows for electric customers who generate a portion of their electricity using fuel cell systems to send excess electricity back to the grid." Fuel cells do not always benefit from net metering policies. For example, Connecticut includes all types of fuel cells in its net metering policies, whereas New York and Rhode Island limit net metering to fuel cells running on renewable fuels (such as biogas).

2) **Renewable Portfolio Standards (RPS)** regulate the types of energy used to generate a state's electricity. Through its RPS, the state sets a required clean energy quota that electricity companies must meet. The state determines which clean energy technologies it wishes to promote. Six states have included fuel cells in their RPS: Connecticut, Delaware, New York, and North Carolina include all fuel cell technologies in their RPS, while California and Massachusetts require fuel cells to run on renewable fuels to qualify under their RPS.

3) **State tax incentives** encourage individuals and businesses to purchase fuel cell vehicles or stationary fuel cells to reduce harmful pollution (in most cases, these tax credits are available for a variety of clean energy sources, not just fuel cells). Authorities recognize that fuel cells, as a zero-emissions power source, offer public benefits (or positive externalities, in economic terms) and seek to reward their use. Several states offer a tax credit for fuel cell purchases. Details can be found at www.dsireusa.org.

4) **Grants, loans, and other incentives** benefiting fuel cells are widespread. California is funding hydrogen station development, as well as operation and maintenance costs. California also has a Self-Generation Incentive Program that provides rebates for qualifying distributed energy systems. Fuel cells represent 24 percent of the program's total installed capacity through 2012 (the latest year for which figures are available). Connecticut is offering several incentives for innovative manufacturers, is partially funding development of two hydrogen stations in the state, and has provided a $10 million, low interest loan to Connecticut-based FuelCell Energy to help it expand its Torrington manufacturing facility. New York's $1 billion Green Bank debuted in February 2014 and is poised to provide low-cost financing for clean energy such as fuel cells. New Jersey established an Energy Resilience Bank in 2014 for distributed energy and backup power projects, and the New Jersey Board of Public Utilities runs a Combined Heat & Power and Fuel Cell Program.

CONCLUSION

Fuel cells are a promising technology, with the potential to play an important role as the economy weans itself away from fossil fuels. Their technical challenges can be addressed with more research and development. Indeed, though fuel cells have been around for a long time, they have had less investment than batteries or combustion engines, and so are a much less mature technology. This means fuel cells will likely continue to improve. Manufacturers are already reducing the quantity of platinum needed in their PEM systems, or eliminating it altogether. They are also making fuel cell support systems cheaper, more reliable, and more compact. Once the technical obstacles are overcome, more widespread commercialization will bring economies of scale, which will help push prices down (the same thing that is happening for battery-powered electric vehicles).

This fact sheet is available electronically (with hyperlinks) at *www.eesi.org/papers*.

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