U.S. Department of ENERGY | Office of Energy Efficiency & Renewable Energy

Vehicle Technologies Office

Hydrogen Fuel Cell Electric Vehicles

A customer fuels their Toyota Mirai FCEV at a hydrogen dispensery in California,
Photo by Dennis Schroeder, NREL 46487

A hydrogen fuel cell electric vehicle (FCEV) is two to three times more efficient than a comparable internal combustion engine running on gasoline.[1] Because of their efficient operation, FCEVs can travel long distances with less fueling. An FCEV also produces clean tailpipe exhaust, emitting only water and warm air.

FCEVs have driving ranges of more than 300 miles per tank of hydrogen.[2] Drivers can fuel their FCEVs in less than five minutes at a dispenser that looks and feels similar to gasoline dispensers except for the high-pressure gaseous connection.[1] In addition, FCEVs are propelled by an electric motor, so they are quiet, have very few moving parts and fewer fluids to change, and have minimal maintenance requirements overall.

What is Hydrogen Fuel?

Hydrogen (H_2) is an alternative fuel that produces zero tailpipe carbon emissions. Hydrogen can be produced from diverse, domestic resources, as it is sourced from water (H_2O), hydrocarbon fuel (i.e., natural gas, renewable liquid fuels, gasified coal, and gasified biomass), and organic matter. As a vehicle fuel, hydrogen is stored as a compressed gas inside high-pressure tanks at 35 MPa (5,000 psi) or 70 MPa (10,000 psi).

How is Hydrogen Produced and Distributed?

Hydrogen can be produced using several processes. Currently, most hydrogen produced in the United States comes from steam methane reforming (SMR), a process that combines high-temperature steam with natural gas to extract the hydrogen. Hydrogen can

Government and industry research and development projects are working toward efficient hydrogen distribution. For example, the U.S. Department of Energy (DOE) established H2@Scale to advance affordable hydrogen production, transport, storage, and use to decarbonize the U.S. economy. This initiative includes DOE-funded projects and national laboratory and industry co-funded activities to accelerate early-stage research, development, and demonstration of applicable hydrogen technologies. Learn more about this initiative at energy.gov/eere/fuelcells/h2scale.

[1] *Fuel Cell Electric Vehicle Durability and Fuel Cell Performance*. Jennifer Kurtz, Sam Sprik, Genevieve Saur, and Shaun Onorato. National Renewable Energy Laboratory, March 2019. (https://www.nrel.gov/docs/fy19osti/73011.pdf)

[2] *Fuel Cell Electric Vehicle Driving and Fueling Behavior*. Jennifer Kurtz, Sam Sprik, Genevieve Saur, and Shaun Onorato. National Renewable Energy Laboratory, March 2019. (https://www.nrel.gov/docs/fy19osti/73010.pdf)

also be produced from water through electrolysis (a process that splits water molecules into hydrogen and oxygen). Electrolysis can be powered by renewable energy sources like wind or solar, which prevents emissions associated with other production methods.

One of the challenges of producing hydrogen is to cost-effectively extract it from these compounds and then transport it to where it is needed. In the United States, most hydrogen is produced close to where it is used or onsite—typically at large industrial sites. Because hydrogen can be produced from a diverse array of resources, regional hydrogen production can maximize local resources and minimize distribution challenges.

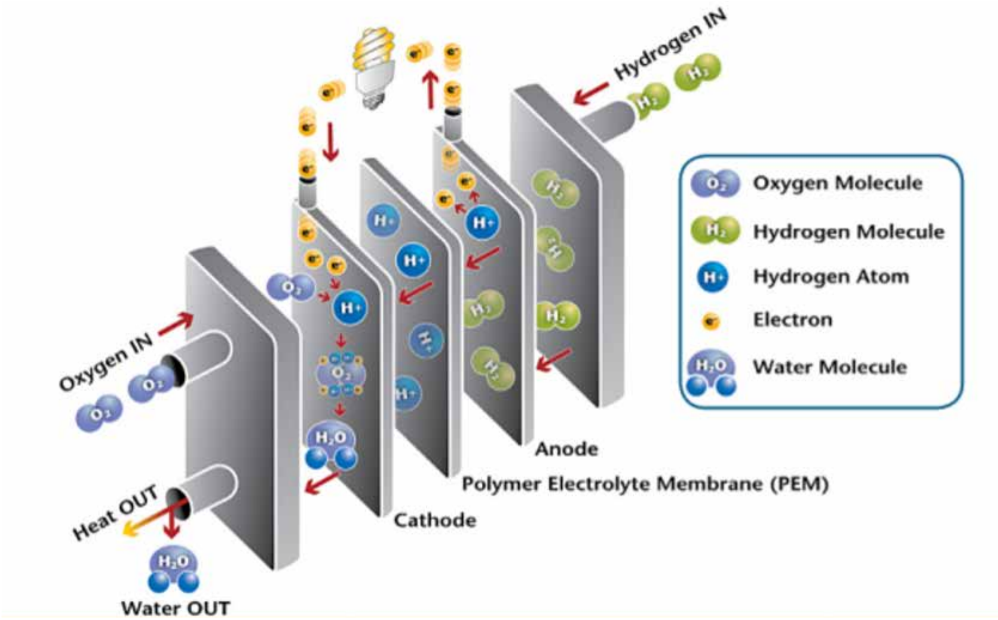


Figure 1. Fuel cells directly convert the chemical energy in hydrogen to electricity, producing pure water and potentially useful heat as the only byproducts. Hydrogen-powered fuel cells are not only pollution-free but are more than two times as efficient as traditional combustion technologies. *Illustration by the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office.*

How is Hydrogen Distributed?

Hydrogen is currently distributed through three methods:

- **Pipeline**: Although the least expensive way to deliver large volumes of hydrogen, there are presently about 1,600 miles of pipelines available for hydrogen delivery in a few U.S. locations, compared to more than 64,000 miles of pipelines for refined petroleum products.
- **High-Pressure Tube Trailers**: Transporting compressed hydrogen gas by truck, railcar, ship, or barge in high-pressure tube trailers is not cost-effective and used primarily for distances of 200 miles or less and common where demand is at a smaller scale or emerging.
- **Liquefied Hydrogen Tankers**: Super-cooled or "cryogenic" liquefied hydrogen can be transported more efficiently than gaseous hydrogen over longer distances by truck, railcar, ship, or barge, but liquefying the hydrogen is currently energy intensive.[3]

For the most part, outside of California the infrastructure needed for distributing hydrogen to a nationwide network of fueling stations is in the process of being developed. Wide-scale growth of hydrogen as a transportation fuel will require advancements of delivery technologies to address key challenges including reducing cost, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage. Delivery infrastructure needs and resources will vary by region, hydrogen market, and increasing demand.

[3] *Annual Report Mileage for Hazardous Liquid or Carbon Dioxide Systems*. Pipeline and Hazardous Materials Safety Administration, October 2024. (https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-hazardous-liquid-or-carbon-dioxide-systems)

How Do FCEVs Work?

In an FCEV, hydrogen gas (H_2) and oxygen (O_2) from air undergo an electro-chemical reaction within a fuel cell to produce electricity, which is used to power an electric motor to propel a car—similar to what happens in a battery electric vehicle. In hydrogen FCEVs, hydrogen is stored as a fuel in a tank. Unlike EVs, FCEVs do not need to use plug-in capabilities to charge the batteries. Instead, batteries serve to smooth out the power delivered from the fuel cell, recapture braking energy, and provide extra power during acceleration.

Most FCEVs are equipped with advanced technologies to increase efficiency, such as regenerative braking systems that capture the energy lost during braking and store it in the battery. And, like other EVs, FCEVs benefit from having very few moving parts. Range and fueling time are also similar to those of today's gasoline vehicles. FCEVs can convert the chemical energy in the hydrogen fuel directly to electrical energy with efficiencies capable of exceeding 60%.[1] Because a fuel cell is two to three times as efficient as today's conventional internal combustion engine, an FCEV can travel the same distance using less than half the energy on-board a gasoline car.

Are Hydrogen FCEVs Safe?

FCEVs are tested to the same rigorous safety standards required for conventional vehicles (e.g., via crash tests). Additionally, the fuel tanks on FCEVs are subjected to numerous tests to ensure that they can withstand impacts, fires, and punctures beyond what normal daily driving or accidents would naturally produce. Hydrogen sensors and leak detection technologies, as well as durable hydrogen tanks for storage, result in vehicles that are as safe as gasoline vehicles. For more information on codes and standards related to hydrogen and FCEVs, as well as other useful information for first responders, visit H2Tools.org.

What Hydrogen FCEVs are Available?

Preliminary efforts are under way to build hydrogen fueling infrastructure and produce FCEVs that are practical for widespread use. As consumer interest grows, major manufacturers have begun developing and producing FCEVs, although they are currently only available in limited markets with hydrogen fueling infrastructure, which is mainly in California. Toyota is selling and leasing the Mirai and Hyundai is selling and leasing the Nexo. Honda, General Motors, Mercedes-Benz/Ford, and BMW have all committed to putting FCEVs on the road in the future.

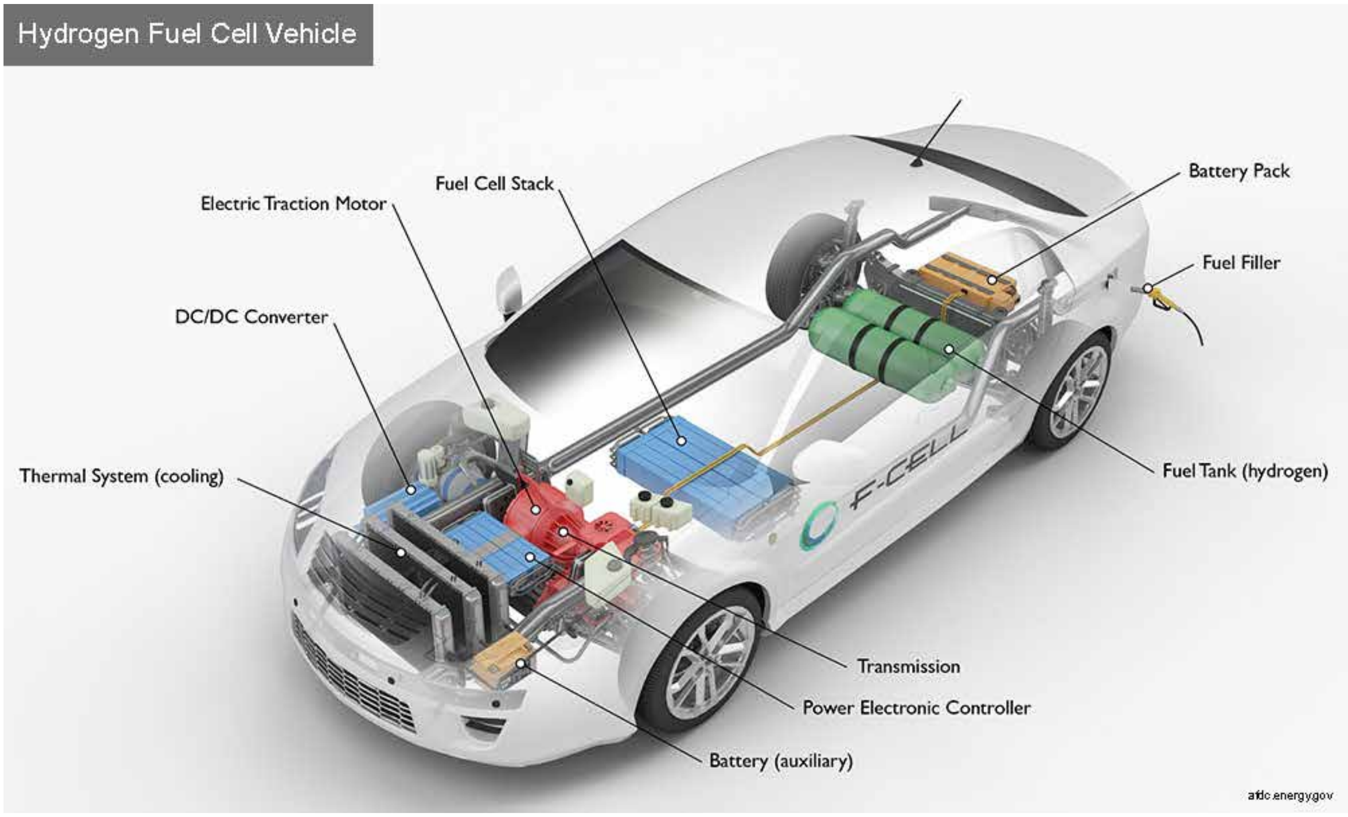


Figure 2. Components of a Hydrogen Fuel Cell Electric Vehicle. *Illustration by Josh Bauer, NREL*

Manufacturers are also tapping into the potential for FCEVs in medium- and heavy-duty applications, where hydrogen's high energy density and fast-fueling capability show promise. FCEVs are currently available for fleet applications including transit buses, shuttle buses, and street sweepers. Some manufacturers, such as Cummins, Daimler, Hyundai, Kenworth, Navistar, Nikola, and Toyota, have also begun developing Class 8 trucks powered by hydrogen, providing another emerging market for hydrogen fuel cells.

To find available FCEVs, see the Alternative Fuels Data Center (AFDC) Vehicle Search at afdc/energy.gov/vehicles/search.

DOE leads research to make hydrgen-powered vehicles an affordable, environmentally friendly, and safe transportation option for all. For more information about fuel cell research and development efforts visit Hydrogen and Fuel Cell Technologies Office website energy.gov/eere/fuelcells.

Figure 3. The National Renewable Energy Laboratory is conducting third party evaluations of hydrogen fuel cell electric bus fleets in California. *Photo by Leslie Eudy, NREL 54541.*

How Do Hydrogen FCEV Emissions Compare with Those of a Conventional Vehicle?

Emitting only water vapor and warm air, an FCEV is a zero-emission vehicle and does not produce criteria pollutants that contribute to smog and poor air quality, such as nitrogen oxides, volatile organic compounds, or particulate matter. However, life cycle emissions may be produced during hydrogen production, and these vary depending on how the fuel is produced. For example, compared to conventional gasoline vehicles, FCEVs can reduce carbon dioxide emissions by 50% when the hydrogen is produced from natural gas, and by 90% if the hydrogen is produced using renewable energy sources, such as wind and solar.[4]

How Do You Fuel a Hydrogen FCEV?

Hydrogen fueling is very similar to fueling a conventional gasoline or diesel vehicle. As a gaseous fuel, hydrogen is dispensed through a sealed fueling connector and hose assembly. The nozzle securely connects to the receptacle of the vehicle forming a tight seal. Fueling can be stopped at any time by turning off the dispenser. Sensors, dispenser-to-vehicle communications, and meters ensure safe and accurate fueling. Once the tank is filled the nozzle is removed and returned to the dispenser.

A woman fuels her Toyota Mirai, FCEV, at a hydrogen fueling station in La Canada Flintridge, California. Fueling an FCEV is a similar experience to fueling at a present-day gas station; drivers can lock the nozzle into place and fill their tank with hydrogen fuel in generally three to five minutes. *Photo by Dennis Schroeder, NREL 46446*

How Do You Fuel a Hydrogen FCEV?

If you are considering purchasing an FCEV, it's important to determine whether hydrogen fueling infrastructure is available in locations that are convenient for you. According to the AFDC Alternative Fueling Station Locator (afdc.energy.gov/locator/stations/), there were almost 60 public retail fueling stations as of 2024 located primarily in California. Before going to a hydrogen fueling station, FCEV drivers check the Hydrogen Fuel Cell Partnership's Station Status website (m.h2fcp.org/) to verify fueling availability at the closest stations.

[4] *Fuel Choices for Fuel-Cell Vehicles: Well-to-Wheels Energy and Emission Impacts.* Michal Wang. Argonne National Laboratory, November 2002. (https://doi.org/10.1016/S0378-7753(02)00447-0)

Hydrogen is dispensed at 10,000 psi (70 MPa) for light-duty vehicles and 5,000 psi (35 MPa) for medium- and heavy-duty vehicles. Dispensers are labeled as H70 or H35 for light-duty vehicles or medium- and heavy-duty vehicles, respectively. The Alternative Fueling Station Locator (afdc.energy.gov/stations) provides information on pressure by individual station.

How Much Does Hydrogen Fuel Cost?

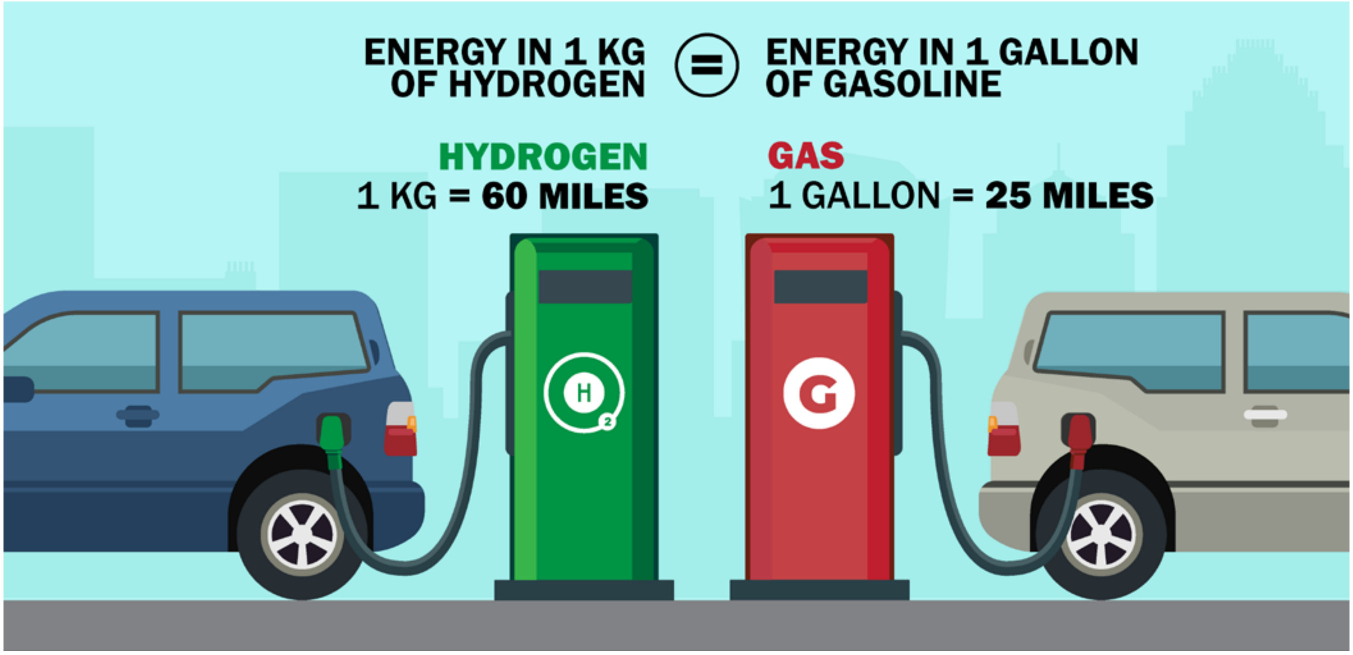
Hydrogen is sold per kilogram, which has about the same energy content as a gallon of gasoline. As of 2023, hydrogen at public stations is selling for about $24–$36 per kilogram.[5] An FCEV with 1 kilogram of hydrogen can drive approximately 60 miles, compared to conventional vehicles, which can drive 25 miles on a gallon of gasoline.

As technologies advance and costs decrease, hydrogen fuel will become more accessible and affordable.

Government and industry leaders are working to address the challenge of fuel cost for everyday consumers. It is worth noting that original equipment manufacturers (OEMs), like Toyota, are currently including three years of hydrogen fuel at no additional cost with their initial sales and lease offerings, shielding early market adopters from this initially high fuel price. In addition, DOE launched the Hydrogen Shot program through the Energy Earthshots Initiative to reduce the cost of producing clean hydrogen by 80% to $1 per 1 kilogram in 1 decade (“1 1 1”). For more information, visit the Hydrogen Shot program page (energy.gov/eere/fuelcells/hydrogen-shot).

Expanding Public Hydrogen Fueling Stations

California is leading the nation by funding the effort to build retail hydrogen fueling stations, and in 2022 the first public stations were built without government funding. With careful planning, the focus has been to add hydrogen fuel at existing gasoline stations covering regions in northern California near San Francisco and southern California near Los Angeles. In addition to continuing the necessary network developments in established markets, there is a significant market opportunity to prioritize development in underserved, disadvantaged communities across California, especially the San Joaquin Valley and the Inland Desert region[6], and the United States. Work is also under way to expand hydrogen fueling locations in Hawaii and across the East coast, with other markets expected to develop to encourage consumer demand for FCEVs. These efforts are giving early FCEV adopters confidence that they can drive normally and have access to hydrogen wherever they go within these regions.



Because FCEVs are more efficient than a comparable gasoline vehicle, hydrogen FCEVs travel longer distances using less energy. *Illustration by the U.S. Department of Energy’s Hydrogen and Fuel Cell Technologies Office.*

[5] *Joint Agency Staff Report on Assembly Bill 8: 2023 Annual Assessment of the Hydrogen Refueling Network in California*. Miki Crowell and Andrew Martinez. California Energy Commission and California Air Resources Board, December 2023. CEC-600-2023-069 (https://www.energy.ca.gov/sites/default/files/2023-12/CEC-600-2023-069.pdf)

[6] 2022 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development. California Air Resource Board, September 2022. (https://ww2.arb.ca.gov/sites/default/files/2022-09/AB-8-Report-2022-Final.pdf)

Expanding Private Hydrogen Fueling Stations

In addition to public stations, there are private stations supporting fleets, with some used for demonstration or research. Mobile hydrogen fuelers, where liquefied or compressed hydrogen and dispensing equipment is stored onboard a trailer, are sometimes deployed to support the expansion of hydrogen infrastructure. As hydrogen fueling station capacity increases, OEMs have the opportunity to accelerate FCEV deployment in established and emerging markets.

Reducing Hydrogen Fueling Station Cost

Initial hydrogen stations were built at about $2 million to $3 million. However, states like California have seen the cost of stations per dispenser decrease 77%–88% from 2012 to 2020 likely due to the increase in station daily fueling capacity and reductions in fueling components cost (economies of scale). In 2020, DOE estimated the cost to be closer to $1.9 million and dropping.[7]

The availability of stations providing reasonably priced hydrogen in places where vehicles will be deployed remains a key challenge to the adoption of this technology. To address this, transportation stakeholders, such as OEMs, have set goals to expand hydrogen fueling station network. In addition, several federal and state incentives include funding for hydrogen fueling infrastructure development and purchasing FCEVs. Funding opportunities and incentives can be found on the AFDC Laws and Incentives Search (afdc.energy.gov/laws/search).

There are almost 60 retail hydrogen fueling stations available to drivers nationwide, although most are concentrated in California. *Photo by Dennis Schroeder, NREL 46428*

Where Can I Learn More About Hydrogen and FCEVs?

To learn more about hydrogen as a transportation fuel, visit the AFDC Hydrogen Fuels and Vehicles pages (afdc.energy.gov/fuels/hydrogen.html). You can also contact your local Clean Cities and Communities coalition director (cleancities.energy.gov/coalitions) or visit the DOE Increase Your H2IQ page (https://www.energy.gov/eere/fuelcells/increase-your-h2iq) and the DOE Hydrogen Tools Portal (https://h2tools.org/). For hydrogen case studies, see the AFDC Case Studies webpage (afdc.energy.gov/case).

[7] *Hydrogen Fueling Stations Cost*. Mariya Koleva and Marc Melania. U.S Department of Energy, February 2021. (https://www.hydrogen.energy.gov/pdfs/21002-hydrogen-fueling-station-cost.pdf)

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