Creating Clean Energy for Future Transportation

Proton Exchange Membrane Fuel Cells Can Use Hydrogen to Maximize Vehicle Range, Efficiency, and Sustainability

Executive Summary

Fuel cells offer a more sustainable way to generate electricity for a variety of applications. They also deliver better fuel efficiency, operating range, durability, and reliability than other power sources, such as combustion engines and batteries.

Among fuel cells available today, proton exchange membranes (PEMs) have become an effective choice in energy generation, especially when used for transportation and material handling applications. In the future, fuel cells may be the main choice to power vehicles.

An Environmentally Sustainable Power Source

Fuel cells convert a fuel source into electricity. When that fuel source is carbon-free, like hydrogen, their only by-products are heat and water. Because they have no mechanical parts, they do not wear down and will operate reliably as long as a fuel source is available. This kind of clean and reliable power generation is appealing for many industries, from utilities to backup power systems to transportation.

Some industries have already started to apply them. In transportation, fuel cells are being deployed in vehicles and ships in combination with batteries. These can operate as hybrid systems, where the fuel cell and battery generate a comparable amount of power, or a system where the fuel cell does most of the work.

Advantages of Fuel Cells Over Batteries and Gas Engines

More industries are adopting fuel cells because they can use different fuel sources and have operational advantages[1] over conventional power sources, such as batteries and combustion engines. These advantages include:

Range and Ease of Refueling

Unlike batteries, fuel cells don't need separate charging steps that can take hours and put a vehicle out of commission when refueling. Fuel cells can refuel almost as quickly as traditional gas engines, taking less than five minutes.[2] Once filled to capacity, a vehicle powered by a fuel cell can drive over 300 miles before the next refuel.[3]

Efficiency

To double the capacity of a battery, the size of the battery itself must be doubled. However, a fuel cell only needs extra fuel to double its capacity. Therefore, for applications where payload is important (such as long-haul trucking), fuel cells are more efficient in terms of payload weight per mile traveled.[4] Furthermore, fuel cells convert the chemical energy of fuel directly into useful electrical energy. By contrast, internal combustion engines must first liberate that energy as heat and transmit it mechanically incurring efficiency losses in the process. Overall, fuel cells operate two to three times more efficiently than diesel and gas internal combustion engines.

Sustainability

Because fuel cells running on hydrogen emit only water and heat, the air around their environment is clean and safe to breathe. Alternatives like combustion engines emit pollution—such as toxins, particles, and greenhouse gases (GHGs)—from burning hydrocarbon fuels.

Versatility

Fuel cells can also be modified to suit the desired application. This includes adjusting the amount of power they deliver, depending on whether they're supporting single vehicles, bus fleets, or utility grids powering entire neighborhoods. Stationary fuel cell systems can even help balance the energy grid by providing supplementary power when intermittent power sources—like renewables—can't match energy demand.[6]

1Source: https://www.energy.gov/eere/fuelcells/early-adoption-fuel-cell-technologies

2Source: https://afdc.energy.gov/vehicles/fuel_cell.html

3Source: https://www.energy.gov/eere/videos/energy-numbers-fuel-cell-electric-vehicles

4Source: https://www.energy.gov/sites/prod/files/2014/03/f9/thomas_fcev_vs_battery_evs.pdf

5Source: https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

6Source: http://www.fchea.org/stationary

Different Types of Fuel Cells

Since Charles Langer and Ludwig Mond first coined the term "fuel cell" in 1889, a wide range of fuel cells have entered the market. Different types of fuel cells[7] include:

- **Alkaline Fuel Cells** (AFCs) operate on compressed hydrogen and pure oxygen with a liquid electrolyte. They were used to provide electricity and drinking water in Apollo spacecraft.[8]

- **Molten Carbonate Fuel Cells** (MCFCs) appeared on the market in the 1960s and ran on fossil fuels. They use high temperature, salt carbonate compounds as the electrolyte. MCFCs are largely used in fuel cell power plants at mega-watt capacity.

- **Phosphoric Acid Fuel Cells** (PAFCs) were among the earliest commercially developed fuel cells and use a liquid phosphoric acid electrolyte contained in a silicon carbide matrix. This type of fuel cell is often used in stationary power generators in the 100 to 400kW range.

- **Solid Oxide Fuel Cells** (SOFCs) have their electrolyte composed of a solid ceramic compound of metal oxides and typically operate at a very high temperature (>500°C [932°F]).

- **Proton Exchange Membranes** (PEMs)—also called Polymer Electrolyte Membranes—use a solid polymer membrane as the electrolyte that conducts protons. This type of fuel cell is often used in transportation and some stationary applications. They're particularly suitable for use in passenger vehicles, such as cars and buses.

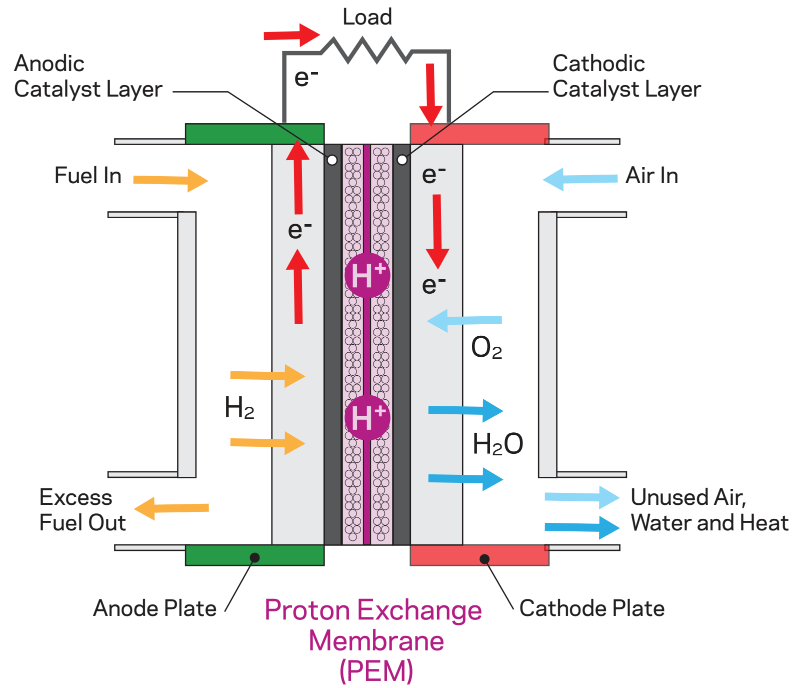
7Source: https://www.energy.gov/eere/fuelcells/types-fuel-cells
8Source: https://airandspace.si.edu/collection-objects/fuel-cell-apollo-4

How Proton Exchange Membrane Fuel Cells Work

The most common type of PEM fuel cell operates on pure hydrogen gas, typically generated from steam methane reforming or electrolysis of water. Other than hydrogen, they need only oxygen (from the air) and water to work.

A PEM fuel cell's energy conversion is performed by two chemical reactions separated by an electrolyte membrane.[9] Each chemical reaction occurs at a specific electrode: one electrode is called the anode (positively charged), and the other is the cathode (negatively charged). Hydrogen gas enters the anode, and oxygen enters the cathode through air flow.

With the help of a platinum catalyst, hydrogen is broken down into protons and electrons at the anode. The electrons travel through an external circuit providing usable electricity, while the protons travel through the PEM. Protons and electrons recombine with oxygen on a platinum catalyst at the cathode to make water. As previously stated, water and heat are the only wastes emitted.



9Source: https://www.energy.gov/eere/fuelcells/parts-fuel-cell

Forward Movement with Proton Exchange Membrane Fuel Cells in Transportation

The adoption of hydrogen-powered PEM fuel cells has already begun. This is due in part to the operational efficiencies[10] and sustainable qualities of PEMs, which make them viable alternatives to traditional power sources in transportation industries. These industries include:

Automotive and Light-Duty Vehicles

The most immediately viable PEM fuel cell applications for light-duty vehicles are return-to-base fleets, such as buses, taxis, and other company-owned vehicles. This is because fleets of vehicles can operate using centralized hydrogen refueling stations, instead of stations spread across many routes. Additionally, PEMs are a sustainable and cost-efficient investment for fleets in public transportation because they exceed the energy efficiency of combustion engines and eliminate GHG emissions. According to the McKinsey report,[11] by 2050, hydrogen could power a global fleet of 400 million cars, 15-20 million trucks, and 5 million buses.

Though PEM cost and fueling station availability is challenging for the privately owned automotive market, many major automotive companies are deploying test fuel cell electric vehicles (FCEVs). Deployments are mainly in California,[12] where hydrogen fueling stations are currently available. As costs come down and refueling becomes more available, adoption rates of privately owned vehicles and other light-duty applications will increase.

10Source: https://www.energy.gov/eere/fuelcells/early-adoption-fuel-cell-technologies
11Source: https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf
12Source: https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf

Heavy-Duty Vehicles, Buses, and Long-Haul Trucks

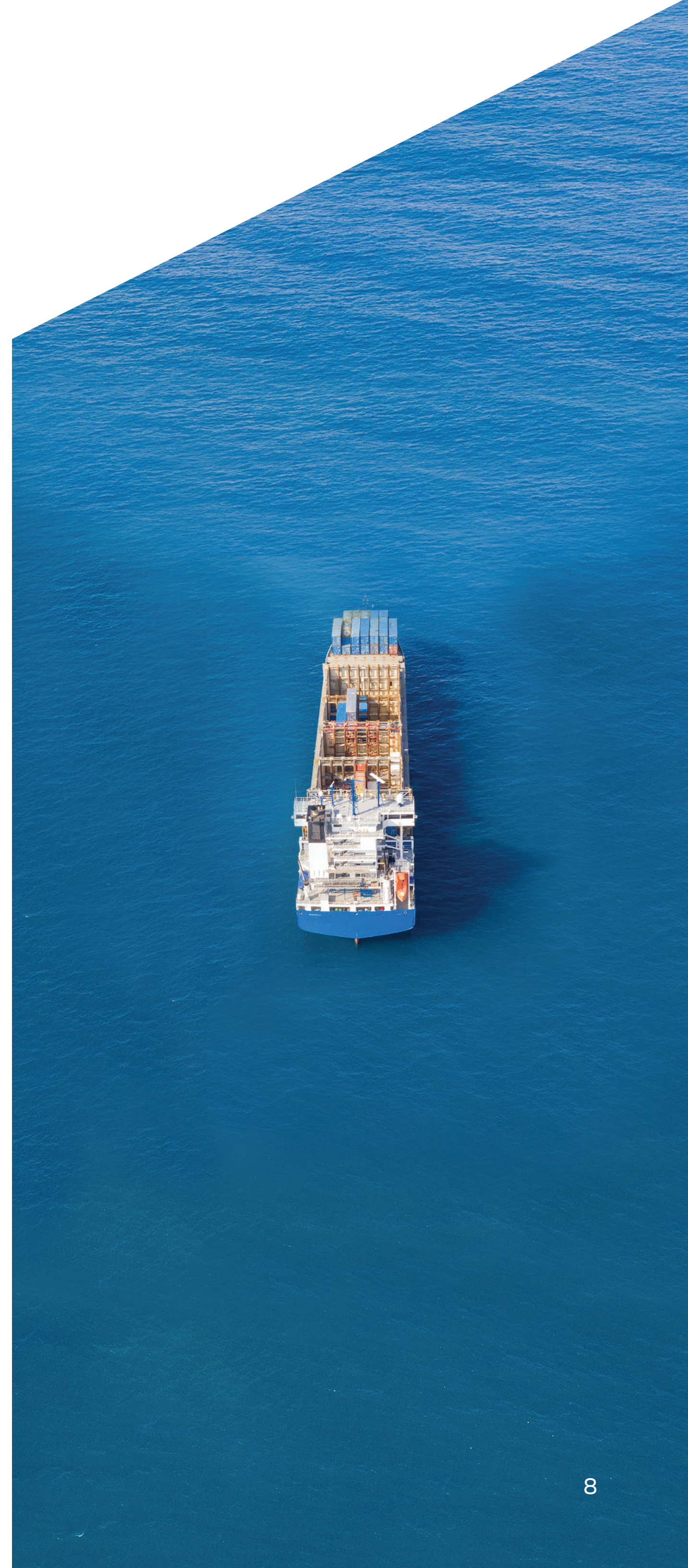
PEM fuel cells can easily support the long-range driving of heavy-duty vehicles, like long-haul trucks and bus fleets, for two main reasons. The first reason being larger vehicles can easily accommodate the current space needed for the PEM fuel cell and fuel. The second reason is because manufacturing PEM fuel cells to support a longer driving range doesn't increase their size or weight. In comparison, the size and weight of batteries must increase significantly when supporting a longer driving range.

Plans are underway to set up hydrogen fueling stations[13] along many major distribution routes used by long-haul trucks and other heavy-duty vehicles carrying shipments. These convenient stations will make long-distance travel more reliable when using fuel cell power. Enabling more heavy-duty vehicles to adopt fuel cells will reduce pollution from the roadways, as diesel emissions from many heavy-duty vehicles create smog that negatively impacts the environment.

Marine Vessels

The marine shipping industry contributes 3% of all global emissions[14] and is a well-known source of GHG emissions. This is due in part to the low-grade fuel marine vessels use, which is responsible for particulate emissions. Particulate emissions are a type of pollution that affects climate change and increases health risks for populations living along coasts.[15]

But, in the past few decades, different types of marine vessels have adopted fuel cell power to eliminate these harmful emissions. As of 2019, a California-based company called Golden Gate Zero Emission Marine began construction on a passenger ferry running entirely on PEM fuel cells.[16] The ferry will tap the public transportation potential of San Francisco waterways, easing the strain on legacy commuting systems and reducing total emissions.



13Source: https://energypost.eu/hydrogen-fuel-cell-trucks-can-decarbonise-heavy-transport

14Source: https://www.transportenvironment.org/press/shipping-emissions-17-global-co2-making-it-elephant-climate-negotiations-room

15Source: https://www.sciencedirect.com/science/article/pii/S1361920915001169

16Source: https://ggzeromarine.com

Many shipping fleet owners and engineers have become enthusiastic since the San Francisco ferry project. Though some engineers have worried about accommodating the larger-sized fuel, as hydrogen is about four times larger than diesel for each unit of energy. However, less units are needed because each unit of hydrogen produces much more power than equivalent units of diesel.[17] Because less fuel is needed and the combustion engines on board will be removed, larger amounts of useful space will be available on marine vessels. Similar projects are now underway in Norway and France. Additionally, fuel cells have even found their way into luxury super-yachts.[18]

Material Handling

As of 2018, over 20,000 fuel cell forklifts are operating in the U.S.[19] These forklifts can work a full eight-hour shift on one tank of hydrogen, refuel in minutes, and operate in refrigerated warehouses, as lower temperatures don't hinder fuel cell performance. Operating facilities of some of the largest retailers—Walmart, Amazon, and General Motors, to name a few—now use hydrogen forklifts in their warehouses.

Unmanned Aerial Vehicles and Aviation

Because engineers in aviation must consider aerodynamics and properties of flight, PEM fuel cell's low weight and energy efficiency makes them an optimal clean energy solution. Because they're lighter than batteries and more efficient than engines, unmanned aerial vehicles and drones can fly for longer with PEM fuel cells.

Though commercial flight hasn't yet been made available with fuel cells, air taxis powered by hydrogen could be produced by 2021.[20] This future form of public transportation could likely provide a greater range of travel for intercity commutes.

17Source: https://www.npr.org/2019/07/16/716693006/the-dawn-of-low-carbon-shipping

18Source: https://www.forbes.com/sites/billspringer/2019/10/01/367-foot-long-hydrogen-powered-superyacht-concept-makes-waves-at-the-monaco-yacht-show/#309a7791efcd

[19]Source: https://www.energy.gov/eere/fuelcells/fact-month-november-2018-there-are-now-more-20000-hydrogen-fuel-cell-forklifts-use

[20]Source: https://www.nbcnews.com/mach/science/electric-air-taxis-powered-hydrogen-promise-greater-range-intercity-commutes-ncna1026981

A Future Driver for Transportation

In the future, fuel cells may be the main choice to power transportation, replacing fossil fuel-powered vehicles with hydrogen-powered buses, trucks, cars, trains, airplanes, and freight ships.

As new uses and applications appear on the market, companies will need an innovative membrane partner to ensure that fuel cells meet performance and reliability requirements for their applications. Such innovative partners already exist and are reinventing the market.

Nafion™ is a leader in the market space, using industry-leading technology to continue developing leading solutions for fuel cells. In fact, Nafion™ ion exchange membranes were the first of their kind and are still the most widely distributed PEM material in the world. Additionally, the history and manufacturing scale of Nafion™ makes it the most dependable brand to ensure the necessary scale at reasonable costs into the future.

Reinventing the Energy Market with Nafion™ Membranes

With over 50 years of experience, the Nafion™ membranes and dispersions team has the knowledge to lead the energy industry on the journey toward a safer, cleaner world. Nafion™ ion exchange membranes have been the products of choice for chlor-alkali electrolysis, providing unparalleled performance and durability. Today, Nafion™ membranes also offer leading-edge solutions for energy storage, fuel cells, water electrolysis, ultrahigh purity chemical production, and other specialty applications.

Nafion™ membranes by Chemours deliver:

Superior chemical stability and proton conductivity

The structure of Nafion™ membranes consists of a flexible, hydrophobic backbone that provides excellent mechanical and chemical stability, while its pendent groups deliver high proton conductivity.

Adaptability for alternative electrolyte systems

Built from Chemours' strong knowledge base and industry experience, Nafion™ membrane properties—like ion conductivity and crossover—are tunable at various levels using monomer, polymer, and membrane processing techniques.

Proven performance from industry-leading field experience

Nafion™ ion exchange membranes have served as the benchmark material across several industries.

It's time to let the future in. Won't you join us?

Visit **Nafion.com** or call one of our technical experts:

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More Benefits of Nafion™ Membranes for Electrolysis Applications

- Durable
- Deliver high performance
- Operate in caustic and low voltage environments
- Retain their properties over time
- Well suited to applications where intermittent renewable energy is used

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