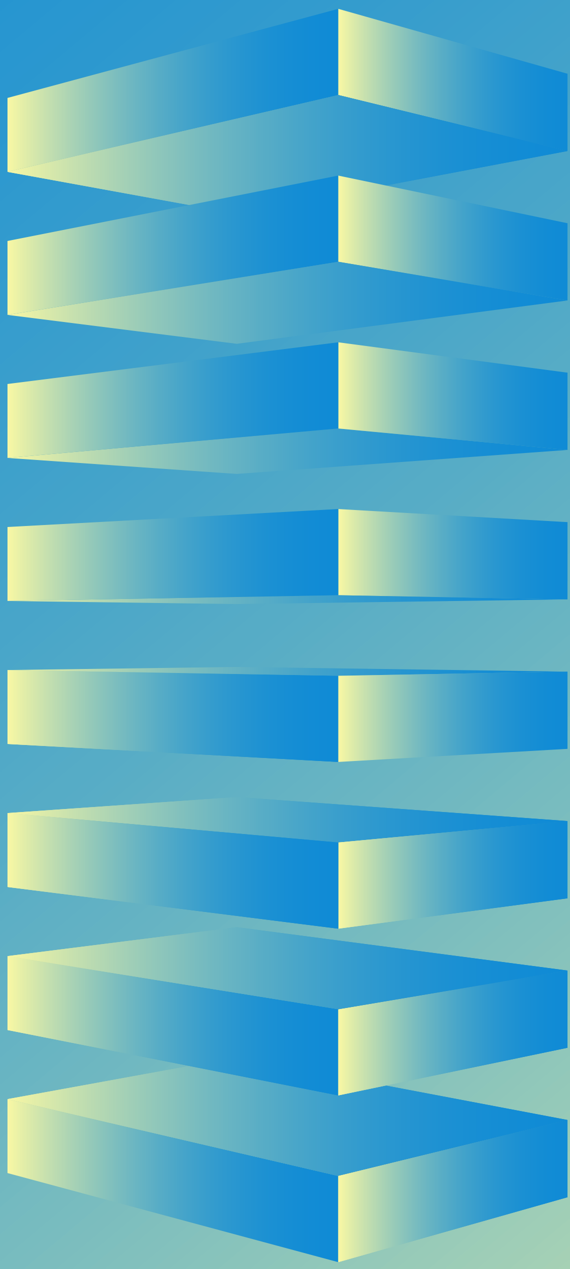
Fuel Cells

Prime Movers Lab
September 2020



Prime
Movers
Lab

Table of Contents

Summary and Outlook

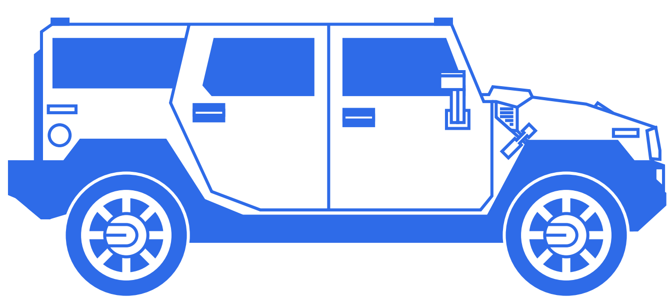
Key takeaways from each section.

Fuel Cell Technology

- Fuel cells produce electricity from a fuel (often hydrogen) and oxygen, with water as the byproduct. They convert fuel to electricity more efficiently than combustion engines or natural gas power plants.
- Proton Exchange Membrane Fuel Cells (PEMFCs) are the most widely produced type of fuel cell, but they can only run on pure hydrogen. These fuel cells are used in most vehicles, and some small remote backup systems.
- Solid Oxide Fuel Cells (SOFCs) and Molten Carbonate Fuel Cells (MCFCs) can be run on natural gas and other fuels in addition to hydrogen. Because these systems run at temperatures of 600–1000 degrees C, the fuel is converted or "reformed" into hydrogen plus other molecules before reaching the fuel cell. SOFCs and MCFCs are mostly used to generate electricity at stationary facilities.

Fuel Cells: Vehicles

- The total number of fuel cell electric vehicles (FCEVs) in the world is small, similar to the number of battery electric vehicles on the road in 2010.
- Hydrogen refueling infrastructure is also nearly non-existent today. There were approximately 470 H_2 fueling stations *worldwide* in 2019, compared to 25,000 EV charging stations and 120,000 gas stations in the US alone. While a nation-wide system for delivering electricity already exists to allow charging stations to be installed anywhere, the same is not true for hydrogen.
- There are increasing efforts to build out hydrogen fueling stations and distribution systems, particularly in Europe and Asia (China, Korea, and Japan).
- The one area where fuel cell vehicles have gained significant traction is FORKLIFTS. You can't have emissions in enclosed warehouses where forklifts operate, and battery charging is time-consuming and requires more space.



- The main barriers to FCEVs becoming more economical are the need for platinum in PEMFC fuel cells (the primary type of fuel cell used in vehicles), the lack of widespread hydrogen infrastructure, improving system designs (how to store H_2 on the vehicle most efficiently), and scaling into markets where large demand may not exist.
- Over the next ten years, FCEVs may make inroads into long haul trucking and outcompete battery electric vehicles (BEVs), but only if a) the cost and availability of distributed hydrogen improves, and b) there are incentives to decarbonize transportation.

Fuel Cells: Stationary Applications

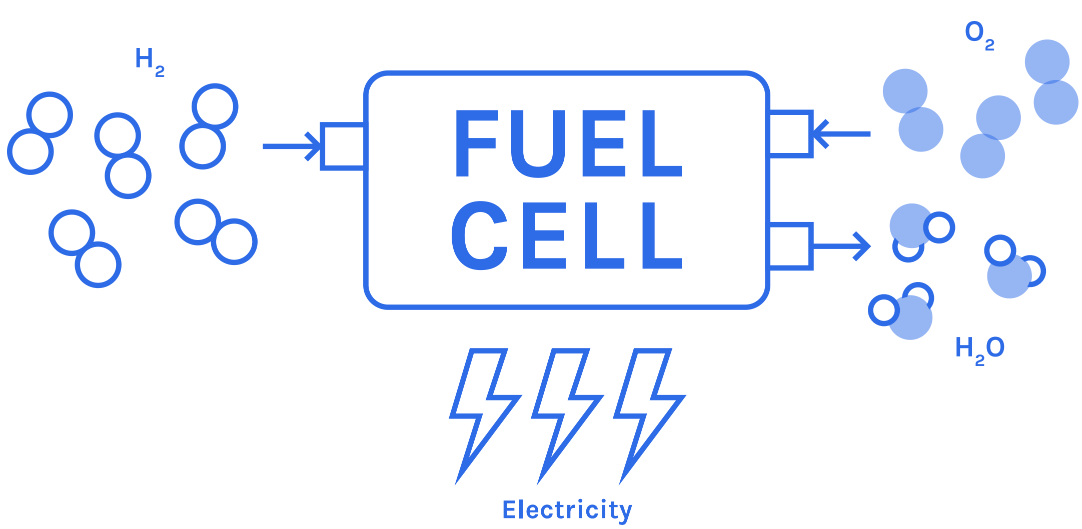
- Fuel cells provide a reliable source of backup power for hours to days. For remote facilities (e.g. telecommunication towers), the fuel used to generate power is often hydrogen stored on site. The emissions and fuel cost are lower than they would be with a diesel generator.
- If natural gas distribution lines are available, some fuel cell systems can generate electricity from the natural gas grid indefinitely. In some areas with high electricity costs, fuel cell systems tied to the natural gas grid enable electricity price hedging in addition to long-term backup power.
- The stationary fuel cell landscape contains many mature players, including multinationals like Bosch, global hydrogen companies like Nel ASA, and strong fuel cell specific technology providers like Plug Power, Bloom Energy, FuelCell Energy, Hydrogenicity, and Ballard Power Systems.
- The next decade will see huge growth in the grid energy storage sector, and hydrogen storage + fuel cells are one option. The variety of energy storage system sizes, site requirements and local resources along with the large amount of growth will permit multiple winners. However, fuel cells are a difficult area for an early-stage startup to succeed in.

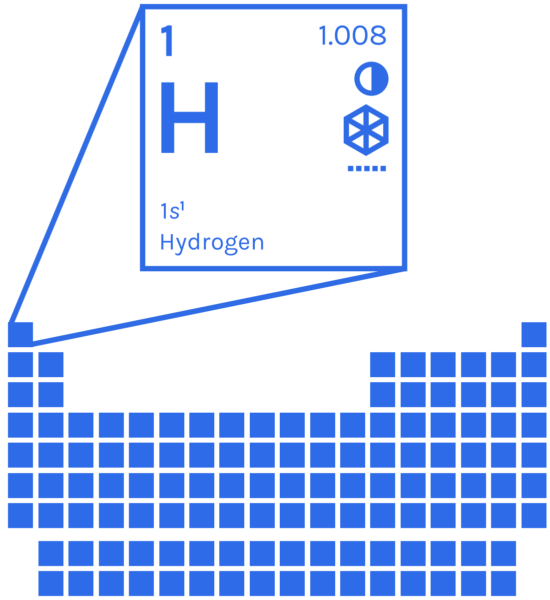
Introduction

Currently there is a fairly sharp line between the worlds of electric power and the hydrocarbon fuels (oil and gas) we use for transportation and industrial heat. Hydrogen doesn't play a big role in providing electricity or as a transportation fuel at the moment, but its role is set to expand, especially in Europe. Looking ahead, hydrogen could provide a solution for both sides of our energy needs: as a flexible form of energy storage to support the electric grid, and as a transportation fuel.

At various times over the last 40 years, there has been a movement to transition to hydrogen as an energy currency. Why? Hydrogen (H_2) is incredibly versatile. Like oil and gas, hydrogen can be transported in pipelines and are stored indefinitely in containers (batteries have some rate of "self discharge", where they slowly lose charge over time). Hydrogen is a key raw material in chemicals production, especially fertilizer.

However, the largest driver for expanding the use of hydrogen is to reduce CO_2 emissions and address climate change. Replacing oil and gas with hydrogen (H_2) would allow us to reduce or eliminate CO_2 emissions from two particularly hard areas, the transportation sector and heavy industry. **Fuel cells** are an exciting way to "decarbonize" the transportation sector, and also enable energy to be stored as hydrogen.





Fuel cells convert hydrogen and oxygen directly to electricity without emissions and with lower energy losses than combustion engines. They can be small, and can be scaled up or down easily. This means hydrogen+fuel cells can be used to run mobile equipment, including vehicles and buses, forklifts, or even space shuttles.

Modern fuel cell technology was first used by NASA in the 1960s to generate electricity for satellites and space capsules, including the Space Shuttle program. With concerns about "peak oil" in the early 2000s, some postulated that hydrogen would be the ideal energy currency for the world. In this "Hydrogen Economy", fuel cells could efficiently convert hydrogen into electricity where it was needed. Much of the core IP around fuel cells and several industry-leading fuel cell companies (Plug Power, Bloom Energy) were founded during this period.

This summer (2020) saw renewed buzz in a future hydrogen economy and fuel cell vehicles. Europe adopted an ambitious plan to go carbon neutral by 2050 - the associated hydrogen strategy dramatically ramps up green hydrogen production and funds fuel cell initiatives. The US fuel cell vehicle company Nikola repeatedly made headlines with its highly publicized SPAC, a roller coaster initial trading period, and finally scandal around claims about its semitruck's functionality (including a promo video showing a semitruck in motion that turned out to be just rolling downhill).

In this briefing, we'll cover the basics of fuel cell technology, the main "flavors" of fuel cell technology in use today, and some of the many exciting applications of fuel cells - both today and in the future.

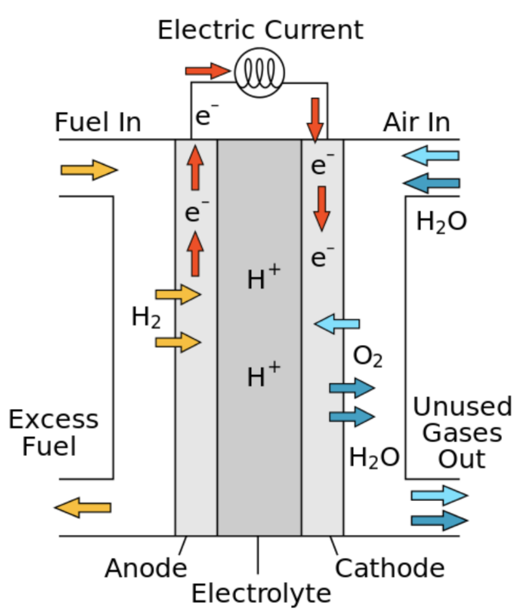
Fuel Cells Turn Fuel Into Electricity

Fuel cells turn fuel Into electricity and water without burning it. Inside a fuel cell, the fuel (hydrogen, natural gas, or other high-energy molecules) reacts electrochemically with oxygen to make water. These reactions cause electrons to move from one side of the fuel cell to the other, generating an electric current. Think of a fuel cell like a battery cell, but with fuel and oxygen feeding into each side. Fuel cells can in theory power anything that requires on electricity — vehicles, buildings, devices, forklifts, and of course spacecraft.

In fuel cell vehicles like Nikola's proposed semi-truck, the electricity produced by the fuel cell powers the motor. Both fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) use electric motors, hence why Nikola and other fuel cell vehicle makers may offer both a fuel cell and a BEV version of a truck.

Inside a fuel cell are the same basic parts as a battery:

1 An **anode**, where the hydrogen (or other fuel) is separated into electrons and ions. The electrons leave the anode through a wire to go power things (like a truck).
2 An **electrolyte**, which is basically a bridge that allows ions to cross but not electrons. If the electrolyte is a liquid, the fuel cell may include a spacer or support.
3 A **cathode**, where electrons are returned to the system. Oxygen is consumed here.



Schematic for a typical PEM fuel cell used in vehicle applications. (Image Source)

Fuel cells ultimately make power by allowing hydrogen and oxygen to recombine and make water. (Fuel cells are basically the opposite of hydrogen electrolyzers, which start with water and use electricity to make hydrogen and oxygen).

On the surface, this seems complicated - why not just burn the H_2 in an internal combustion engine (ICE) like we burn gasoline or diesel? Wouldn't the emissions from burning hydrogen in air still just be water?

The main reason is that fuel cells are more efficient than combustion engines. Fuel cells convert up to 60% or more of the energy in the fuel into power, compared to roughly 40% for diesel engines and just 20% to 35% for cars running on gasoline. In traditional car engines (ICEs) most of the energy in the fuel is wasted as heat. The fuel cell gives you 1.5 to 3 times the amount of energy (or 1.5 to 3 times the miles traveled) for the same amount of fuel! [1]

A second reason is that burning hydrogen in an ICE or industrial boiler creates high temperatures (think of all that wasted heat), which turns some of the nitrogen and oxygen in the air into smog (NOx) in side reactions.

Selecting the Right Fuel Cell for the Job

Both batteries and fuel cells use different materials and chemicals depending on the product requirements. For example, smartphones use lithium-ion batteries (energy dense), flashlights use alkaline batteries (cheap), and gas-powered vehicles have a lead-acid starter battery (cheap and long-lived). Even Li-ion batteries, which all shuttle lithium ions back and forth, use different cathode materials depending on whether the product demands higher power, longer time between charges, or more charge/discharge cycles. (*Check out our partner Dan's blog posts and Kids' Corner video on how batteries work!*)

Similarly, different types of fuel cells are best suited for different situations. All fuel cells ultimately make power by allowing hydrogen and oxygen to recombine and make water. However, many fuel cells for stationary power generation or backup power are designed to accept natural gas or even diesel rather than just pure hydrogen. Some types of fuel cells are okay with certain contaminants in the fuel or air. Let's briefly explore the options that exist today.

As a reminder, all fuel cells have three basic parts: an **anode** (on the fuel side), a **cathode** (on the side with oxygen), and an **electrolyte** with support between them that lets ions across. Different types of fuel cells have been developed over the years that use different materials for each part. Fuel cell vehicles typically use Proton Exchange Membrane fuel cells (PEMFCs), shown on the left—in these cells, hydrogen ions (protons) cross the electrolyte to meet oxygen. In contrast, the materials in solid oxide fuel cells (SOFCs) result in oxygen ions crossing over to the hydrogen side, and water is made at the anode instead (see image on the right).

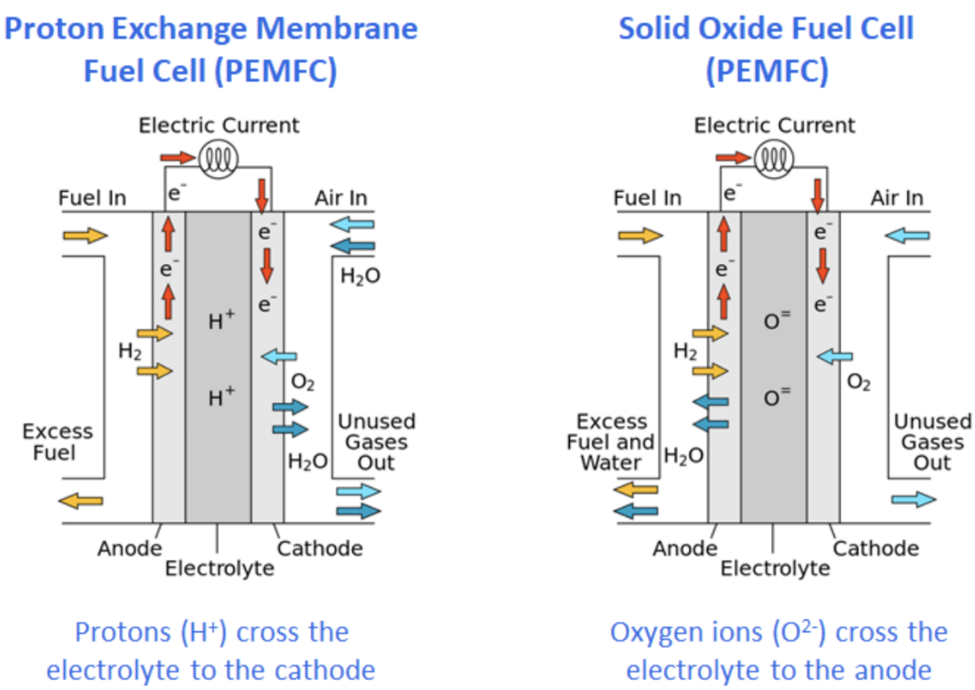


Image Credit: Sakurambo - Own work (Image Source: Left, Right)

There are five major types of fuel cell technologies in use:

Proton Exchange Membrane Fuel Cells (PEMFCs) are used in vehicles due to their high power density—they weigh less and take up less space for the same power compared to other fuel cells. The electrolyte in PEMFCs is a proton-conducting **polymer** (picture a thin sheet of plastic). The first PEMFCs were enabled by the discovery of the polymer Nafion at duPont in the 1960s. The anode and cathode are made of porous carbon with platinum (Pt) that plays an important role in the chemical reaction. The platinum is the most expensive material in the fuel cell.

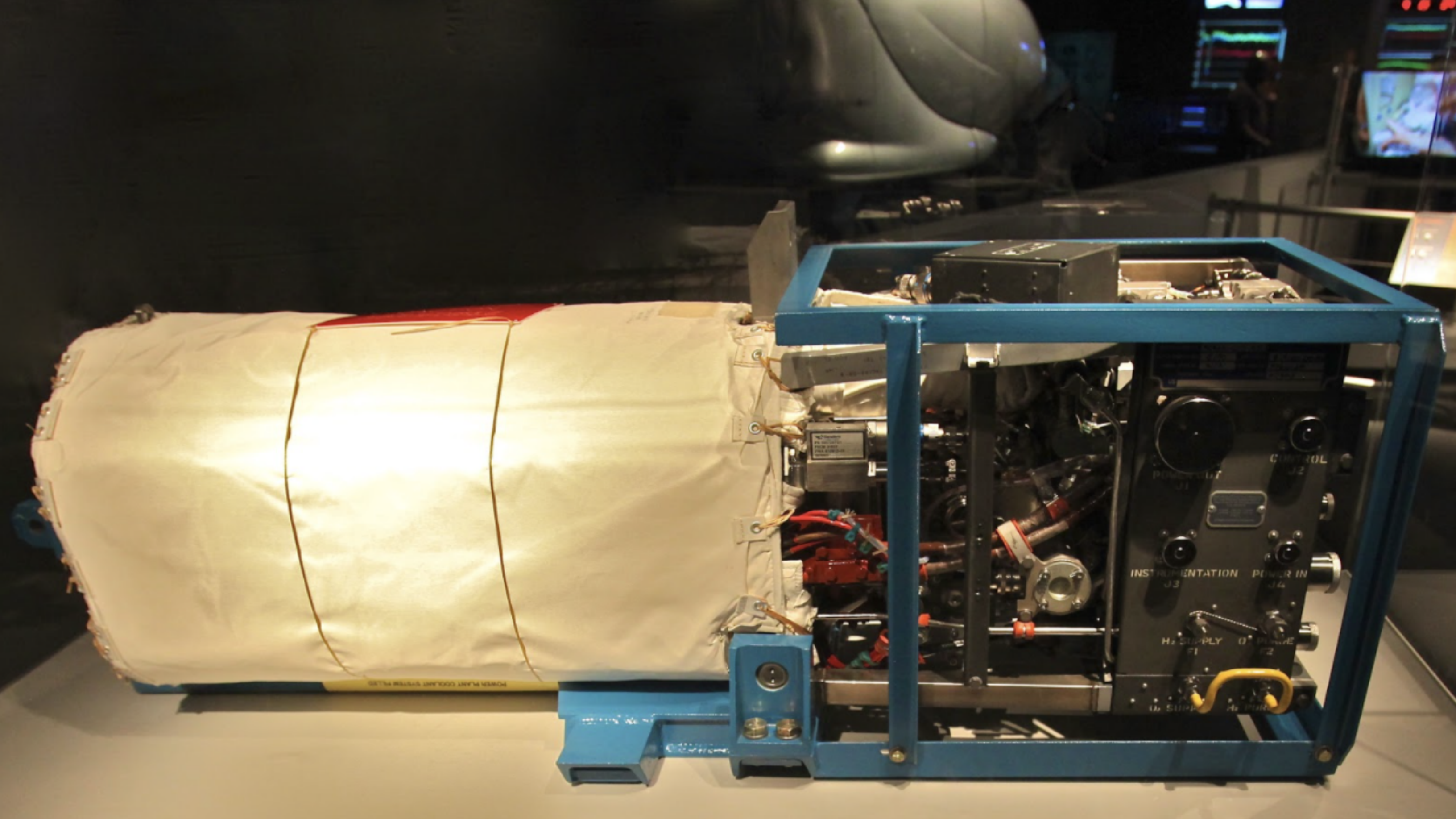
PEMFCs are operated at low temperatures (<100 deg C) partly because the polymer's performance goes down at higher temperatures. Running at low temperatures allows PEMFCs to start quickly, which is especially good for vehicles—they don't have to heat up. Low temperature operation also leads to better durability, and reduces heat losses. The downside of operating at low temperatures is that platinum ($$$) is needed to split hydrogen into protons and electrons at that temperature. Platinum is also "poisoned" by carbon monoxide, which is present when most fuels other than pure hydrogen are used. [2] However, scientists have found ways to get more power with less platinum [3], and are working on ways to remove platinum entirely. [4]

PEMFCs are currently the most widely produced type of fuel cell, making up 67.7% of the fuel cells shipped in 2019. Because PEMFCs operate at relatively low temperatures, are smaller than other fuel cells, and have a short warm-up time, they are the fuel cell used in fuel cell vehicles and forklifts, as well as telecommunications and home backup power systems.

Alkaline Fuel Cells (AFCs) were the O-G fuel cell technology. NASA began using AFCs on the Apollo-series missions in the mid-1960s, and continued using AFCs to provide power and drinking water on the Space Shuttle until the program ended in 2012. These fuel cells use water with potassium hydroxide (KOH) as the electrolyte. Because CO_2 can dissolve in the aqueous KOH electrolyte, AFCs need to be supplied pure oxygen or air with the CO_2 removed. [5] Since using pure oxygen rather than air is much more expensive and the original AFCs also used platinum ($$$), AFCs did not gain widespread traction for other applications.

The key advantages of AFCs are that they can reach efficiencies of 70% or more, higher than PEMFCs. In addition, new types of AFCs are in development that recirculate the KOH electrolyte through the cell, addressing some of the challenges around electrolyte loss and poisoning.

Solid Oxide Fuel Cells (SOFCs) are currently less widely used than PEMFCs, but have several advantages for large, stationary applications. As their name suggests, solid oxide fuel cells are made entirely of solid components, including the electrolyte that allows ions to cross the cell. This eliminates many problems caused by liquid electrolytes. [6] The solid ceramic electrolytes in SOFCs can also operate at much higher temperatures than PEMFCs and AFCs: 800–1000 degrees C. This both eliminates the need for expensive metals like platinum in the electrodes, [7] and allows them to use a variety of fuels- hydrogen, syngas, or natural gas. [8]



A fuel cell assembly from the Space Shuttle Orbiter, retired in 2012. So analog!
[Photo by Steve Jurvetson](#) under CC

Bloom Energy is a high-profile example of a company offering 200 kW and larger SOFCs for backup or recurring power generation from natural gas. The cost of producing electricity with their system can be significantly cheaper than local utility prices in their customers' areas, allowing companies to avoid paying peak rates.

Molten Carbonate Fuel Cells (MCFCs) are mainly used for large megawatt-scale stationary power generation. Like the name suggests, these fuel cells use liquid carbonate salts as the electrolyte, within a porous ceramic material support. They also operate at high temperatures (650 degrees C), allowing them to use fuels other than hydrogen and removing the need for expensive metals in the cathode and anode. Drawbacks include the need to add CO_2 at the cathode (the oxygen side) to replace the carbonate ions in the electrolyte that are consumed in the chemical reactions. FuelCell Energy is one company offering large MCFC systems for stationary power.

Phosphoric Acid Fuel Cells (PAFCs) use phosphoric acid as an electrolyte and operate at moderate temperatures, around 180 degrees C. They are generally more resistant to fuels with carbon monoxide despite using carbon with platinum in the electrodes. However, PAFCs are less efficient for electricity generation than other fuel cells, and contain more platinum per electrode. This type of fuel cell is most used for stationary heat and power generation, but they have also been used in city buses.

Individual fuel cells are assembled into systems. Like battery packs, fuel cell systems are a large number of individual "cells" stacked together in parallel. A single individual fuel cell (an anode, electrolyte, and cathode sandwich) currently produces about a watt of power or less.

Individual fuel cells are coupled into stacks to make larger systems. In batteries, leads (wires) are attached to the electrodes in each cell. Fuel cell engineers have a more difficult challenge: they have to design systems to deliver hydrogen and oxygen gases to each cell in the system. (Adapted from [Bloom Energy])

Fuel cell systems contain many components beyond just the fuel cell "stacks". The fuel and oxygen-containing gases have to be cleaned and delivered to and from the fuel cell at the right temperature and pressure. Other equipment converts the electricity generated into the right type of power for the load (e.g., is AC or DC power required?) In stationary power or backup applications that use a fuel other than hydrogen, the fuel has to be "reformed" —heated and broken down into H_2, CO, and CO_2—before reaching the fuel cell.

Fuel Cell Applications: Vehicles

Overall, the potential benefits of fuel cell electric vehicles are 1) greater fuel efficiency, 2) eliminating emissions of carbon dioxide and other pollutants (e.g. smog, particulates), and 3) quick refueling compared to battery charging. The main challenges are the current cost of fuel cell systems and a lack of infrastructure for the production and distribution of hydrogen. So are hydrogen-powered fuel cell vehicles (FCVs) going to take over the highways any time soon?

Fuel Cell Vehicles Today

There are very few FCEVs on the road today. Roughly 8,600 fuel cell electric vehicles (FCEVs) have been sold in the US since 2014 according to Argonne National Lab. In June 2020, 49 FCEVs were sold in the US. Despite these small numbers, the United States is still the world leader in FCEVs on the roads at the moment (1 in 3 FCEVs are in the US), followed by China, Japan, and the Republic of Korea.

For comparison, over 1 million plug-in battery electric vehicles (BEVs) were sold over the same time 2014–2019 period. A total of 4.7 million passenger cars (of any type) were sold in 2019 alone.

FCEVs have a lot of catching up to do. For those interested in joining the rather exclusive club of fuel cell vehicle owners, there are three fuel cell passenger vehicles currently on the market in the US: *Toyota Mirai, Honda Clarity, and Hyundai Nexo.* These three fuel cell passenger cars all have a range of about 300 miles. (They sadly do not meet my requirement of getting to Yosemite National Park and back, a 370 mi roundtrip from Berkeley.)

The current hydrogen fueling station infrastructure for FCEVs is also small, albeit increasing. At the end of 2019, 470 hydrogen refueling stations were in operation worldwide. This represents a 20% increase from 2018. The number of stations in operation expanded considerably in Korea (+20), Japan (+13) and Germany (+12) in 2019. Japan remains the leader with 113 refueling stations, followed by Germany with 81, and the United States with 64 stations.

Compare this to the current EV charging infrastructure. Although there are almost 25,000 charging stations in the US, there are still many would-be Tesla owners with range anxiety. (For reference, there are around 120,000 gas stations in the US.) [9] Also, it is relatively easy to establish an EV charging station, as almost every home and Whole Foods is already on the electric grid. The charging infrastructure and adapters are all that is needed. A hydrogen fueling station requires the infrastructure to handle and dispense a pressurized, flammable gas safely, plus onsite hydrogen storage capacity, and a reliable supply of hydrogen.

This lack of infrastructure can be overcome for fleet operators like city buses and refuse collection. By refueling at a central terminal with a source of hydrogen, this barrier can be eliminated. However, the higher capital and maintenance costs of fuel cell buses currently makes them unattractive without significant regulatory or other economic incentives. To illustrate, in 2019 an average conventional diesel 40-foot bus costed roughly $475,000 and an average compressed natural gas (CNG) bus costed roughly $560,000, compared to fuel cell electric bus costs of $1.3mm at the time and $850,000 predicted in 2021 (NREL blog, June 2019).

The one area where fuel cell vehicles have gained significant traction today is in forklifts and vehicles to move heavy things indoors. You can't have emissions in enclosed warehouses, and battery charging is time consuming and requires more space. Walmart made headlines several years ago for reducing its environmental impact through hydrogen-powered forklifts; many other large companies, including Amazon and Wegman's parent company have followed suit. Today there are over 25,000 hydrogen-powered forklifts in the US.

The Future of Fuel Cell Vehicles

There were roughly the same number of battery electric vehicles on the road in 2010 as there are FCEVs today. Will the next ten years see growth in FCEVs similar to what we saw in plug-in electric vehicles?

If we assume a 20% per year growth in the number of hydrogen fueling stations, the US would only be at about 400 stations in 2030. Rather than attempt to cover the entire

US, companies hoping to build ownership in this space have announced plans for hydrogen fueling "corridors" along trucking routes. Nikola has announced plans to build 700 truck refueling stations in the US and Canada between now and 2028. Shell has been actively building hydrogen refueling stations in California in collaboration with Toyota and Honda, in addition to the 45 stations it operates worldwide (with the majority in Germany). Some governments are also subsidizing or otherwise incentivizing refueling stations for hydrogen powered vehicles.

While we can expect to see many announcements in the press of new hydrogen fueling stations opening, the US hydrogen fuel station network will remain sparse for at least the next five to ten years.

The fuel cell technology used in today's FCEVs, primarily Proton Exchange Membrane Fuel Cells (PEMFCs), is fairly mature. A key cost driver of these fuel cells is the amount of platinum required to make the chemical reactions happen. Unfortunately this raw material cost is unlikely to decrease with increased manufacturing scale, although there are several DOE-sponsored research efforts to decrease the amount of platinum needed. While the lifetime and durability is expected to increase, experts do not expect the absolute cost of PEMFC fuel cells to come down to the extent that lithium-ion batteries did between 2010 and today (a ten-fold decrease).

On the other hand, the engineering design and the optimization of support systems around vehicle fuel cells (compressors, humidifiers, sensors, hydrogen tanks) are less mature. Improvements in this space usually require specialized expertise and intimate knowledge of vehicle manufacturing processes, so they are more likely to come from large automakers than garage startups (although I would love to be surprised here).

To summarize, FCEVs have some distinct advantages over other vehicle types, but are still too costly to compete without subsidies in most cases. The difficulty of building out extensive hydrogen refueling infrastructure will limit the extent of FCEV adoption in the next ten years. However, sufficient momentum is growing to build out enough hydrogen depots and "hydrogen corridors" to further prove out the durability and value of both light-duty FCEV fleets and heavy-duty fuel cell trucks. There is potential for improved fuel cell technologies and continued system optimization to reduce fuel cell costs. If one measures demand for FCEVs by Nikola pre-orders, demand is growing for the first time. Together, these effects (or upward price pressure on lithium) may bring FCEVs into the black in five years.

A hydrogen-powered bus at a public transit station in Fruitvale, CA
[Photo](#) By Cajunlukeca under CC.

As ridesharing and autonomous vehicles further transform the transportation land-scape, perhaps change will come sooner. Lyft could decide to lease FCEVs to all of its drivers. Hydrogen powered autonomous cars could refuel and get back on the road faster than EVs. However for the next few years, you are more likely to see a fuel cell on a forklift at Walmart than on the interstate.

Fuel Cell Applications: Stationary Power

While most of us think of fuel cells powering things that move (transportation and material handling), the largest use of fuel cells in the US is for stationary power generation. These systems turn fuels like hydrogen into electricity for buildings and other users when they can't (or don't want to) pull power from the electric grid. Stationary fuel cell systems range in size from small 1–10 kW systems (enough to power a home) to several megawatts (MW). For comparison, the fuel cell in the Nikola Badger will deliver 120 kilowatts (kW) of power—in the middle of this range.

Current Stationary Fuel Cell Applications

The US alone has over 550 megawatts (MW) of large-scale fuel cell systems that provide non-stop power for key services, such as data centers, telecommunications towers, hospitals, emergency response systems, and military applications. There are also currently over 8,000 small-scale fuel cell systems operating across 40 states, primarily for cell phone towers and remote communications networks. [10] Compared to the diesel generators they often replace, fuel cell systems are cleaner, quieter, pollute less, and require little on-site maintenance. They have a wide operating temperature range, a small footprint, and have no moving parts.

In 2019, stationary fuel cells made up 70% of the global fuel cell market by volume (Grandview estimates this market at $10B currently). After many years of relatively slow growth, the rate of new stationary fuel cell systems is picking up.

Outlook for Fuel Cells in Stationary Applications

Fuel cell power generation systems are experiencing a Renaissance, though there is stiff competition from batteries to provide temporary power as lithium ion battery prices move further down the cost curve. Other forms of long-term chemical energy storage (e.g. Form Energy) and mechanical energy storage (e.g. Amber Kinetics, Quidnet, Energy Vault) have also reached the technology demonstration and early commercial installation stage. The fast growing stationary energy storage space is so large ($30B by 2023) and diverse in its requirements that many companies and approaches will do well.

That said, fuel cells are difficult space for a new startup to enter. In addition to technology multi-nationals (e.g. Bosch, Doosan Fuel Cell), many companies in the fuel cell space are mature public companies; examples include FuelCell Energy (founded in 1969), Ballard Power Systems (f. 1979), Hydrogenics (f. 1995), Plug Power (f. 1997), and

Bloom Energy (f. 2001). They survived the hype cycle of the early 2000s and Cleantech 1.0 bubble, and have reference installations and manufacturing expertise to show for it. These companies spent the last decade or two building technical expertise in fuel cell system design and production, a complicated systems integration problem that requires chemical reactions, materials science, and mechanical engineering.

Startup companies based solely on scientific breakthroughs at the single fuel cell level (improving one or more of the basic fuel cell components: anode, electrolyte, cathode) will have an uphill battle to prove out their product's reliability and cost at scale. While they may earn an early acqui-hire, it is hard to envision an attractive exit path for new venture-backed companies in the fuel cell space. A successful newcomer in this space will need strong contract manufacturing and customer relationships to plug into existing supply chains.

Notes

[1] A helpful breakdown of where the energy in a gasoline-powered car goes can be found here. For comparison, electric motors are about 90% efficient. This article also shows where the hydrogen tank and fuel cell sits in several fuel cell passenger car models.

[2] Eliminating platinum from a PEMFC would allow the fuel cell to run on syngas (a common mixture of hydrogen and carbon monoxide) or reformed natural gas, opening up a wider choice of fuels.

[3] For example, the amount of Pt used in the electrodes was decreased by 20X in the 1980s and 90s. Scientists developed new ways to create super thin layers of Pt, and learned that alloys (mixtures) of Pt and other metals could be effective. Toyota used an alloy of Pt and cobalt (Co) in their 2014 Mirai FCEV. (From Whiston et al 2019 Supplemental Information)

[4] Some research has shown that other metals such as palladium or nickel could be used, but the degradation of these electrodes still needs to be addressed.

[5] Dissolving CO_2 in solutions of water and KOH to make K_2CO_3 is the first step in Carbon Engineering's CO_2 capture process, which was also featured in a previous blog post! Unfortunately for fuel cells, if too much KOH is converted to K_2CO_3, there are not enough OH ions to run the fuel cell — you've lost your electrolyte.

[6] Moving from a liquid to a solid fuel cell electrolyte prevents electrolyte loss due to evaporation, the potential for leakage, and some poisoning concerns.

[7] Fuel cells that run at high temperatures (over 600 degrees C) often include a "reformer" section that uses heat to convert the fuel to hydrogen, carbon monoxide, and carbon dioxide.

[8] Increasing the temperature of a chemical reaction typically increases the number of times that reaction happens per second (called the reaction rate, or more broadly "kinetics"). Running fuel cells at high temperatures increases the reaction rate. The temperatures for both MCFCs and SOFC — over 600 and over 800 degrees C respectively, are high enough that they do not require noble metal catalysts like platinum.

[9] I estimated this from sources suggesting that there are between 107,000 and 150,000 gas stations in the US.

[10] For more information on current fuel cell and hydrogen production facilities in the US, see this comprehensive report from the Fuel Cell and Hydrogen Energy Association.