"WORKING TOWARDS BEING THE BEST"

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Unit:5

Topic: Geothermal energy

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Geothermal energy:

Geothermal energy is thermal energy generated and stored in the Earth. Thermal energy is the energy that determines the temperature of matter. The geothermal energy of the Earth's crust originates from the original formation of the planet and from radioactive decay of materials (in currently uncertain but possibly roughly equal[2] proportions). The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. The adjective geothermal originates from the Greek roots γη (geo), meaning earth, and θερμος (thermos), meaning hot. Earth's internal heat is thermal energy generated from radioactive decay and continual heat loss from Earth's formation.[3] Temperatures at the core–mantle boundary may reach over 4000 °C (7,200 °F).[4] The high temperature and pressure in Earth's interior cause some rock to melt and solid mantle to behave plastically, resulting in portions of the mantle convicting upward since it is lighter than the surrounding rock. Rock and water is heated in the crust, sometimes up to 370 °C (700 °F).

With water from hot springs, geothermal energy has been used for bathing since Paleolithic times and for space heating since ancient Roman times, but it is now better known for electricity generation. Worldwide, 11,700 megawatts (MW) of geothermal power was available in 2013. An additional 28 gigawatts of direct geothermal heating capacity is installed for district heating, space heating, spas, industrial processes, desalination and agricultural applications as of 2010. Geothermal power is cost-effective, reliable, sustainable, and environmentally friendly, but has historically been limited to areas near tectonic plate boundaries. Recent technological advances have dramatically expanded the range and size of viable resources, especially for applications such as home heating, opening a potential for widespread exploitation. Geothermal wells release greenhouse gases trapped deep within the earth, but these emissions are much lower per energy unit than those of fossil fuels. The earth's geothermal resources are theoretically more than adequate to supply humanity's energy needs, but only a very small fraction may be profitably exploited. Drilling and exploration for deep resources is very expensive. Forecasts for the future of geothermal power depend on assumptions about technology, energy prices, subsidies, plate boundary movement and interest rates. Pilot programs like EWEB's customer opt in Green Power Program[9] show that customers would be willing to pay a little more for a renewable energy source like geothermal. But as a result of government assisted research and industry experience, the cost of generating geothermal power has decreased by 25% over the 1980s and 1990s. In 2001, geothermal energy costs between two and ten US cents per kWh

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History of Geothermal energy:

The oldest known pool fed by a hot spring, built in the Qin dynasty in the 3rd century BC

Hot springs have been used for bathing at least since Paleolithic times.[12] The oldest known spa is a stone pool on China's Lisan mountain built in the Qin Dynasty in the 3rd century BC, at the same site where the Huaqing Chi palace was later built. In the first century AD, Romans conquered *Aquae Sulis*, now Bath, Somerset, England, and used the hot springs there to feed public baths and underfloor heating. The admission fees for these baths probably represent the first commercial use of geothermal power. The world's oldest geothermal district heating system in Chaudes-Aigues, France, has been operating since the 15th century. The earliest industrial exploitation began in 1827 with the use of geyser steam to extract boric acid from volcanic mud in Larderello, Italy.

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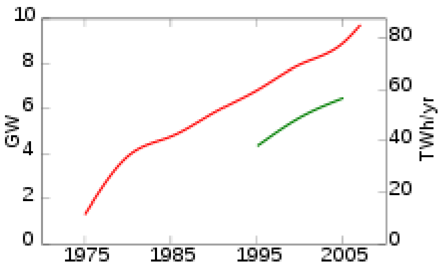
In 1892, America's first district heating system in Boise, Idaho was powered directly by geothermal energy, and was copied in Klamath Falls, Oregon in 1900. The first known building in the world to utilize geothermal energy as its primary heat source was the Hot Lake Hotel in Union County, Oregon, whose construction was completed in 1907.[14] A deep geothermal well was used to heat greenhouses in Boise in 1926, and geysers were used to heat greenhouses in Iceland and Tuscany at about the same time.[15] Charlie Lieb developed the first downhole heat exchanger in 1930 to heat his house. Steam and hot water from geysers began heating homes in Iceland starting in 1943.



Global geothermal electric capacity. Upper red line is installed capacity;[16] lower green line is realized production.

In the 20th century, demand for electricity led to the consideration of geothermal power as a generating source. Prince Piero Ginori Conti tested the first geothermal power generator on 4 July 1904, at the same Larderello dry steam field where geothermal acid extraction began. It successfully lit four light bulbs. Later, in 1911, the world's first commercial geothermal power plant was built there. It was the world's only industrial producer of geothermal electricity until New Zealand built a plant in 1958. In 2012, it produced some 594 megawatts.

Lord Kelvin invented the heat pump in 1852, and Heinrich Zoelly had patented the idea of using it to draw heat from the ground in 1912.[19] But it was not until the late 1940s that the geothermal heat pump was successfully implemented. The earliest one was probably Robert C. Webber's home-made 2.2 kW direct-exchange system, but sources disagree as to the exact timeline of his invention.[19] J. Donald Kroeker designed the first commercial geothermal heat pump to heat the Commonwealth Building (Portland, Oregon) and demonstrated it in 1946.[20][21] Professor Carl Nielsen of Ohio State University built the first residential open loop version in his home in 1948. The technology became popular in Sweden as a result of the 1973 oil crisis, and has been growing slowly in worldwide acceptance since then. The 1979 development of polybutylene pipe greatly augmented the heat pump's economic viability.

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In 1960, Pacific Gas and Electric began operation of the first successful geothermal electric power plant in the United States at The Geysers in California. The original turbine lasted for more than 30 years and produced 11 MW net power. The binary cycle power plant was first demonstrated in 1967 in the USSR and later introduced to the US in 1981. This technology allows the generation of electricity from much lower temperature resources than previously. In 2006, a binary cycle plant in Chena Hot Springs, Alaska, came on-line, producing electricity from a record low fluid temperature of 57 °C (135 °F).

Types of geothermal energy:

Geothermal energy comes in either vapor-dominated or liquid-dominated forms. Larderello and The Geysers are vapor-dominated. Vapor-dominated sites offer temperatures from 240 to 300 °C that produce superheated steam.

1. Liquid-dominated plants

Liquid-dominated reservoirs (LDRs) are more common with temperatures greater than 200 °C (392 °F) and are found near young volcanoes surrounding the Pacific Ocean and in rift zones and hot spots. Flash plants are the common way to generate electricity from these sources. Pumps are generally not required, powered instead when the water turns to steam. Most wells generate 2-10 MWe. Steam is separated from a liquid via cyclone separators, while the liquid is returned to the reservoir for reheating/reuse. As of 2013, the largest liquid system is Cerro Prieto in Mexico, which generates 750 MWe from temperatures reaching 350 °C (662 °F). The Salton Sea field in Southern California offers the potential of generating 2000 MWe. Lower temperature LDRs (120–200 °C) require pumping. They are common in extensional terrains, where heating takes place via deep circulation along faults, such as in the Western US and Turkey. Water passes through a heat exchanger in a Rankine cycle binary plant. The water vaporizes an organic working fluid that drives a turbine. These binary plants originated in the Soviet Union in the late 1960s and predominate in new US plants. Binary plants have no emissions.[18][35]

2. Thermal energy

Main articles: Geothermal heating and geothermal heat pump

Lower temperature sources produce the energy equivalent of 100M BBL per year. Sources with temperatures of 30–150 °C are used without conversion to electricity as district heating, greenhouses, fisheries, mineral recovery, industrial process heating and bathing in 75 countries. Heat pumps extract energy from shallow sources at 10–20 °C in 43 countries for use in space heating and cooling. Home heating is the fastest-growing means of exploiting geothermal energy, with global annual growth rate of 30% in 2005[36] and 20% in 2012.[18][35]

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Approximately 270 petajoules (PJ) of geothermal heating was used in 2004. More than half went for space heating, and another third for heated pools. The remainder supported industrial and agricultural applications. Global installed capacity was 28 GW, but capacity factors tend to be low (30% on average) since heat is mostly needed in winter. Some 88 PJ for space heating was extracted by an estimated 1.3 million geothermal heat pumps with a total capacity of 15 GW.[7]

Heat for these purposes may also be extracted from co-generation at a geothermal electrical plant.

Heating is cost-effective at many more sites than electricity generation. At natural hot springs or geysers, water can be piped directly into radiators. In the hot, dry ground, earth tubes or downhole heat exchangers can collect the heat. However, even in areas where the ground is colder than room temperature, heat can often be extracted with a geothermal heat pump more cost-effectively and cleanly than by conventional furnaces.[37] These devices draw on much shallower and colder resources than traditional geothermal techniques. They frequently combine functions, including air conditioning, seasonal thermal energy storage, solar energy collection, and electric heating. Heat pumps can be used for space heating essentially anywhere.

Iceland is the world leader in direct applications. Some 92.5% of its homes are heated with geothermal energy, saving Iceland over $100 million annually in avoided oil imports. Reykjavík, Iceland has the world's biggest district heating system, often used to heat pathways and roads to hinder the accumulation of ice.[38] Once known as the most polluted city in the world, it is now one of the cleanest.

3. Enhanced geothermal

Enhanced geothermal systems (EGS) actively inject water into wells to be heated and pumped back out. The water is injected under high pressure to expand existing rock fissures to enable the water to freely flow in and out. The technique was adapted from oil and gas extraction techniques. However, the geologic formations are deeper and no toxic chemicals are used, reducing the possibility of environmental damage. Drillers can employ directional drilling to expand the size of the reservoir. Small-scale EGS have been installed in the Rhine Graben at Soultz-sous-Forêts in France and at Landau and Insheim in Germany.

Geothermal Power plant:

1. Geothermal power:

Geothermal power is power generated by geothermal energy. Technologies in use include dry steam power stations, flash steam power stations and binary cycle power stations. Geothermal electricity generation is currently used in 26 countries,[1] while geothermal heating is in use in 70 countries.

As of 2015, worldwide geothermal power capacity amounts to 12.8 gigawatts (GW), of which 28 percent or 3.55 GW are installed in the United States. International markets grew at an average annual rate of 5 percent over the three years to 2015, and global geothermal power capacity is expected to reach 14.5–17.6 GW by 2020, Based on current geologic knowledge and technology the GEA publicly discloses, the Geothermal Energy Association (GEA) estimates that only 6.9 percent of total global potential has been tapped so far, while the IPCC reported geothermal power potential to be in the range of 35 GW to 2 TW.[2] Countries generating more than 15 percent of their electricity from geothermal sources include El Salvador, Kenya, the Philippines, Iceland, New Zealand, and Costa Rica.

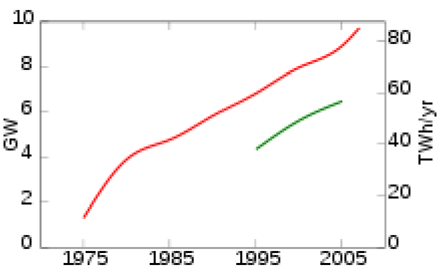
Geothermal power is considered to be a sustainable, renewable source of energy because the heat extraction is small compared with the Earth's heat content.[5] The greenhouse gas emissions of geothermal electric stations are on average 45 grams of carbon dioxide per kilowatt-hour of electricity, or less than 5 percent of that of conventional coal-fired plants.

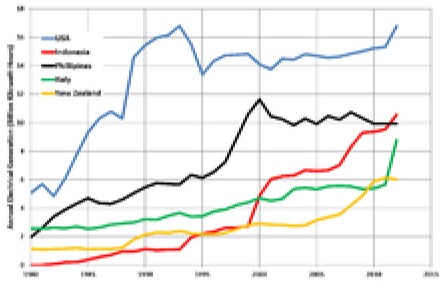
As a source of renewable energy for both power and heating, geothermal has the potential to meet 3-5% of global demand by 2050. With economic incentives, it is estimated that by 2100 it will be possible to meet 10% of global demand.

History and development

In the 20th century, demand for electricity led to the consideration of geothermal power as a generating source. Prince Piero Ginori Conti tested the first geothermal power generator on 4 July 1904 in Larderello, Italy. It successfully lit four light bulbs.[7] Later, in 1911, the world's first commercial geothermal power station was built there. Experimental generators were built in Beppu, Japan and the Geysers, California, in the 1920s, but Italy was the world's only industrial producer of geothermal electricity until 1958.

Trends in the top five geothermal electricity-generating countries, 1980–2012 (US EIA)





Global geothermal electric capacity. Upper red line is installed capacity;[8] lower green line is realized production.

In 1958, New Zealand became the second major industrial producer of geothermal electricity when its Wairakei station was commissioned. Wairakei was the first station to use flash steam technology.[9] Over the past 60 years, net fluid production has been in excess of 2.5 km^3. Subsidence at Wairakei-Tauhara has been an issue in a number of formal hearings related to environmental consents for expanded development of the system as a source of renewable energy.[4]

In 1960, Pacific Gas and Electric began operation of the first successful geothermal electric power station in the United States at The Geysers in California.[10] The original turbine lasted for more than 30 years and produced 11 MW net power.[11]

The binary cycle power station was first demonstrated in 1967 in the Soviet Union and later introduced to the United States in 1981,[10] following the 1970s energy crisis and significant changes in regulatory policies. This technology allows the use of much lower temperature resources than were previously recoverable. In 2006, a binary cycle station in Chena Hot Springs, Alaska, came on-line, producing electricity from a record low fluid temperature of 57 °C (135 °F).

Geothermal electric stations have until recently been built exclusively where high-temperature geothermal resources are available near the surface. The development of binary cycle power plants and improvements in drilling and extraction technology may enable enhanced geothermal systems over a much greater geographical range.[13] Demonstration projects are operational in Landau-Pfalz, Germany, and Soultz-sous-Forêts, France, while an earlier effort in Basel, Switzerland was shut down after it triggered earthquakes. Other demonstration projects are under construction in Australia, the United Kingdom, and the United States of America.[14]

The thermal efficiency of geothermal electric stations is low, around 7–10%,[15] because geothermal fluids are at a low temperature compared with steam from boilers. By the laws of thermodynamics this low temperature limits the efficiency of heat engines in extracting useful energy during the generation of electricity. Exhaust heat is wasted, unless it can be used directly and locally, for example in greenhouses, timber mills, and district heating. The efficiency of the system does not affect operational costs as it would for a coal or other fossil fuel plant, but it does factor into the viability of the station. In order to produce more energy than the pumps consume, electricity generation requires high-temperature geothermal fields and specialized heat cycles. Because geothermal power does not rely on variable sources of energy, unlike, for example, wind or solar, its capacity factor can be quite large – up to 96% has been demonstrated.[16] However the global average capacity factor was 74.5% in 2008, according to the IPCC.

2. Geothermal power plant types:

Geothermal power stations are similar to other steam turbine thermal power stations in that heat from a fuel source (in geothermal case, the Earth's core) is used to heat water or another working fluid. The working fluid is then used to turn a turbine of a generator, thereby producing electricity. The fluid is then cooled and returned to the heat source.

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Dry steam power stations

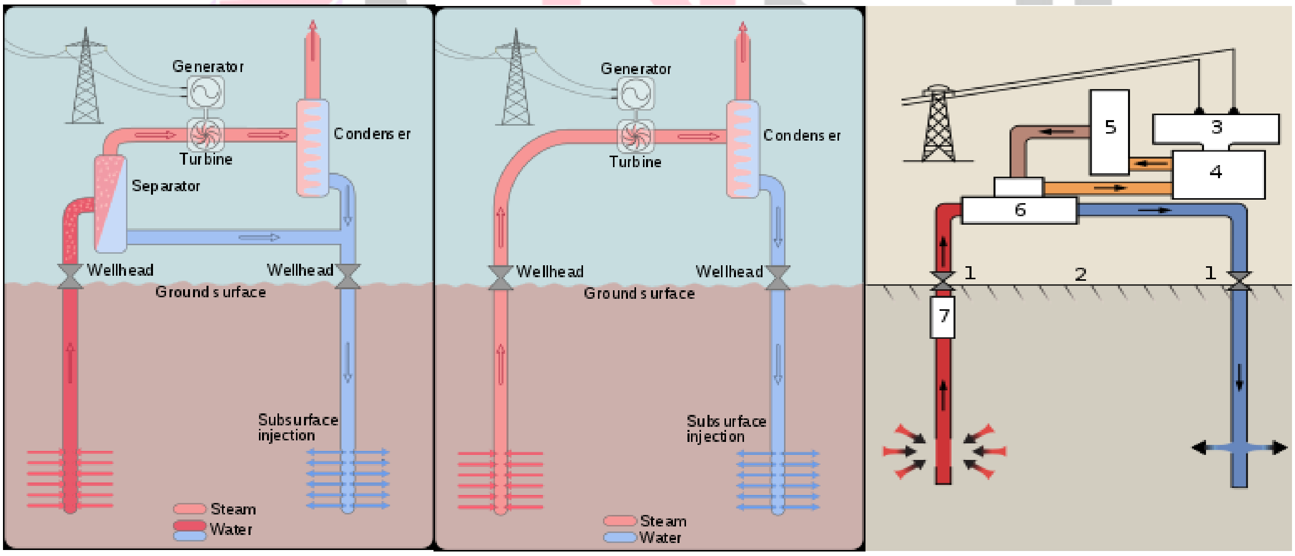
Dry steam stations are the simplest and oldest design. This type of power station is not found very often, because it requires a resource that produces dry steam, but is the most efficient, with the simplest facilities.[24] In these sites, there may be liquid water present in the reservoir, but no water is produced to the surface, only steam.[24] Dry Steam Power directly uses geothermal steam of 150 °C or greater to turn turbines.[2] As the turbine rotates it powers a generator which then produces electricity and adds to the power field.[25] Then, the steam is emitted to a condenser. Here the steam turns back into a liquid which then cools the water.[26] After the water is cooled it flows down a pipe that conducts the condensate back into deep wells, where it can be reheated and produced again. At the Geysers in California, after the first thirty years of power production, the steam supply had depleted and generation was substantially reduced. To restore some of the former capacity, supplemental water injection was developed during the 1990s and 2000s, including utilization of effluent from nearby municipal sewage treatment facilities.

Flash steam power stations

Flash steam stations pull deep, high-pressure hot water into lower-pressure tanks and use the resulting flashed steam to drive turbines. They require fluid temperatures of at least 180 °C, usually more. This is the most common type of station in operation today. Flash steam plants use geothermal reservoirs of water with temperatures greater than 360 °F (182 °C). The hot water flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and used to power a turbine/generator. Any leftover water and condensed steam may be injected back into the reservoir, making this a potentially sustainable resource.[28] [29]

Binary cycle power stations

Binary cycle power stations are the most recent development, and can accept fluid temperatures as low as 57 °C.[12] The moderately hot geothermal water is passed by a secondary fluid with a much lower boiling point than water. This causes the secondary fluid to flash vaporize, which then drives the turbines. This is the most common type of geothermal electricity station being constructed today.[30] Both Organic Rankine and Kalina cycles are used. The thermal efficiency of this type of station is typically about 10–13%.



Environmental impact:

Fluids drawn from the deep earth carry a mixture of gases, notably carbon dioxide (CO_2), hydrogen sulphide.

2S), methane (CH)
4), ammonia (NH)
3), and radon (Rn). If released, these pollutants contribute to global warming, acid rain, radiation, and noxious smells. [failed verification]

Existing geothermal electric stations, that fall within the 50th percentile of all total life cycle emissions studies reviewed by the IPCC, produce on average 45 g of CO
2 equivalent emissions per megawatt-hour of generated electricity (kg CO
2eq/MW·h). For comparison, a coal-fired power plant emits 1,001 g of CO
2 per megawatt-hour when not coupled with carbon capture and storage (CCS).[6]

Stations that experience high levels of acids and volatile chemicals are usually equipped with emission-control systems to reduce the exhaust. Geothermal stations could theoretically inject these gases back into the earth, as a form of carbon capture and storage.

In addition to dissolved gases, hot water from geothermal sources may hold in solution trace amounts of toxic chemicals, such as mercury, arsenic, boron, antimony, and salt.[45] These chemicals come out of solution as the water cools, and can cause environmental damage if released. The modern practice of injecting geothermal fluids back into the Earth to stimulate production has the side benefit of reducing this environmental risk.

Station construction can adversely affect land stability. Subsidence has occurred in the Wairakei field in New Zealand.[46] Enhanced geothermal systems can trigger earthquakes due to water injection. The project in Basel, Switzerland was suspended because more than 10,000 seismic events measuring up to 3.4 on the Richter Scale occurred over the first 6 days of water injection.[47] The risk of geothermal drilling leading to uplift has been experienced in Staufen im Breisgau.
Geothermal has minimal land and freshwater requirements. Geothermal stations use 404 square meters per GW·h versus 3,632 and 1,335 square meters for coal facilities and wind farms respectively.[46] They use 20 litres of freshwater per MW·h versus over 1000 litres per MW·h for nuclear, coal, or oil. Geothermal power stations can also disrupt the natural cycles of geysers. For example, the Beowawe, Nevada geysers, which were uncapped geothermal wells, stopped erupting due to the development of the dual-flash station.

How geothermal power plant works?

There are several different main types of geothermal plants:

- **Dry steam**
- **Flash steam**
- **Binary cycle**

What these types of geothermal power plants all have in common is that they use steam turbines to generate electricity. This approach is very similar to other thermal power plants using other sources of energy than geothermal.

Water or working fluid is heated (or used directly incase of geothermal dry steam power plants), and then sent through a steam turbine where the thermal energy (heat) is converted to electricity with a generator through a phenomenon called electromagnetic induction. The next step in the cycle is cooling the fluid and sending it back to the heat source.

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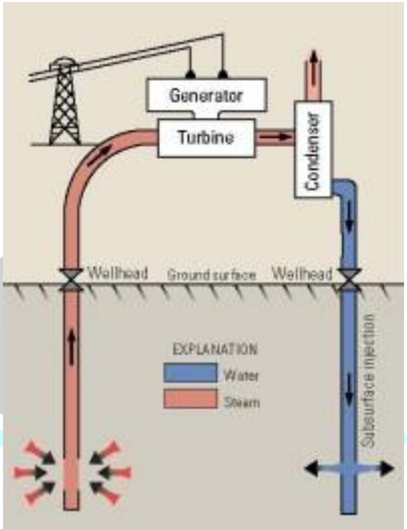
Water that has been seeping into the underground over time has gained heat energy from the geothermal reservoirs. There no need for additional heating, as you would expect with other thermal power plants. Heating boilers are not present in geothermal steam power plants and no heating fuel is used.

Production wells (red on the illustrations) are used to lead hot water/steam from the reservoirs and into the power plant.

Rock catchers are in place to make sure that only hot fluids is sent to the turbine. Rocks can cause great damage to steam turbines.

Injection wells (blue on the illustrations) ensure that the water that is drawn up from the production wells returns to the geothermal reservoir where it regains the thermal energy (heat) that we have used to generate electricity.

Depending on the state of the water (liquid or vapor) and its temperature, different types of power plants are used for different geothermal reservoirs. Most geothermal power plants extract water, in its vapor or liquid form, from the reservoirs somewhere in the temperature-range 100-320°C (220-600°F).



Geothermal Dry Steam Power Plants

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This type of geothermal power plant was named *dry steam* since water water that is extracted from the underground reservoirs has to be in its gaseous form (water-vapor).

Geothermal steam of at least 150°C (300°F) is extracted from the reservoirs through the production wells (as we would do with all geothermal power plant types), but is then sent directly to the turbine. Geothermal reservoirs that can be exploited by geothermal dry steam power plants are rare.

Dry steam is the oldest geothermal power plant type. The first one was constructed in Larderello, Italy, in 1904. The Geysers, 22 geothermal power plants located in California, is the only example of geothermal dry steam power plants in the United States.

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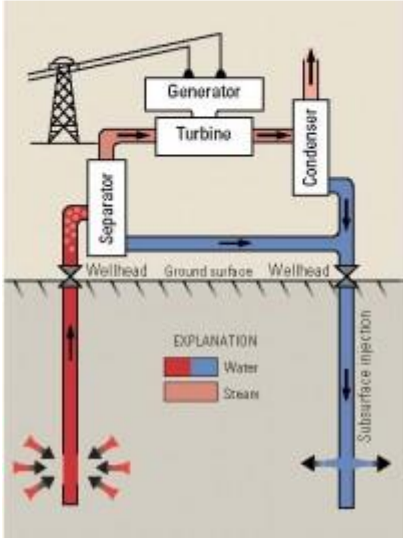
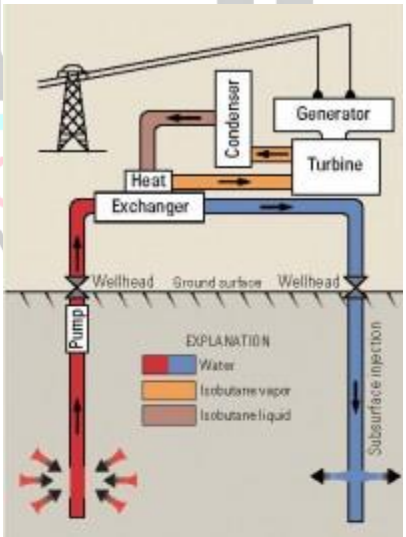


Geothermal Flash Steam Power Plants

Geothermal flash steam power plants uses water at temperatures of at least 182°C (360°F). The term *flash steam* refers the process where high-pressure hot water is *flashed* (vaporized) into steam inside a flash tank by lowering the pressure. This steam is then used to drive around turbines.

Flash steam is today's most common power plant type. The first geothermal power plant that used flash steam technology was the Wairakei Power station in New Zealand, which was built already in 1958:



Geothermal Binary Cycle Power Plants

The binary cycle power plant has one major advantage over flash steam and dry steam power plants: The water-temperature can be as low as 57°C (135°F).

By using a working fluid (binary fluid) with a much lower boiling temperature than water, thermal energy in the reservoir water flashes the working fluid into steam, which then is used to generate electricity with the turbine. The water coming from the geothermal reservoirs through the production wells is never in direct contact with the working fluid. After the some

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of its thermal energy is transferred to the working fluid with a heat exchanger, the water is sent back to the reservoir through the injection wells where it regains it's thermal energy.

These power plants have a thermal efficiency rate of only 10-13%. However, geothermal binary cycle power plants enable us, through lowering temperature requirements, to harness geothermal energy from reservoirs that with a dry- or a flash steam power plant wouldn't be possible.

First successful geothermal binary cycle project took place in Russia in 1967.

Fuel cells:

Hydrogen + Oxygen = Electricity + Water Vapor

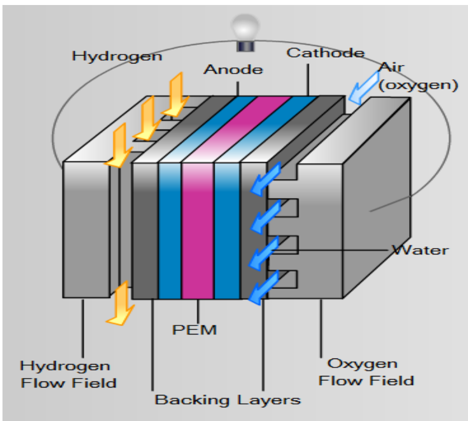
Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Anode: $2H_2 \rightarrow 4H^+ + 4e^-$
Overall: $2H_2 + O_2 \rightarrow 2H_2O$

A fuel cell is a device that converts chemical potential energy (energy stored in molecular bonds) into electrical energy. A PEM (Proton Exchange Membrane) cell uses hydrogen gas (H_2) and oxygen gas (O_2) as fuel. The products of the reaction in the cell are water, electricity, and heat. This is a big improvement over internal combustion engines, coal burning power plants, and nuclear power plants, all of which produce harmful by-products.

Since O_2 is readily available in the atmosphere, we only need to supply the fuel cell with H_2 which can come from an electrolysis process (see Alkaline electrolysis or PEM electrolysis).

There are four basic elements of a PEM Fuel Cell:

The anode, the negative post of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.The cathode, the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water. The electrolyte is the proton exchange membrane. This specially treated material, which looks something like ordinary kitchen plastic wrap, only conducts positively charged ions. The membrane blocks electrons. For a PEMFC, the membrane must be hydrated in order to function and remain stable. The catalyst is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum nanoparticles very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the PEM.



As the name implies, the heart of the cell is the proton exchange membrane. It allows protons to pass through it virtually unimpeded, while electrons are blocked. So, when the H_2 hits the catalyst and splits into protons and electrons (remember, a proton is the same as an H+ ion) the protons go directly through to the cathode side, while the electrons are forced to travel through an external circuit. Along the way they perform useful work, like lighting a bulb or driving a motor, before combining with the protons and O_2 on the other side to produce water.

How does it work? Pressurized hydrogen gas (H_2) entering the fuel cell on the anode side. This gas is forced through the catalyst by the pressure. When an H_2 molecule comes in contact with the platinum on the catalyst, it splits into two H+ ions and two electrons (e-). The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell.

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O).

All these reaction occurs in a so called cell stack. The expertise then also involves the setup of a complete system around core component that is the cell stack.

The stack will be embedded in a module including fuel, water and air management, coolant control hardware and software. This module will then be integrated in a complete system to be used in different applications.

Due to the high energetic content of hydrogen and high efficiency of fuel cells (55%), this great technology can be used in many applications like transport (cars, buses, forklifts, etc) and backup power to produce electricity during a failure of the electricity grid.

Advantages of the technology:

- **By converting chemical potential energy directly into electrical energy, fuel cells avoid the "thermal bottleneck" (a consequence of the 2^{nd} law of thermodynamics) and are thus inherently more efficient than combustion engines, which must first convert chemical potential energy into heat, and then mechanical work.**
- **Direct emissions from a fuel cell vehicle are just water and a little heat. This is a huge improvement over the internal combustion engine's litany of greenhouse gases.**
- **Fuel cells have no moving parts. They are thus much more reliable than traditional engines.**
- **Hydrogen can be produced in an environmentally friendly manner, while oil extraction and refining is very damaging.**

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Types of Fuel cells:

Types of fuel cells; design[edit]

Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three adjacent segments: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electric current is created, which can be used to power electrical devices, normally referred to as the load.

At the anode a catalyst oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electric current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

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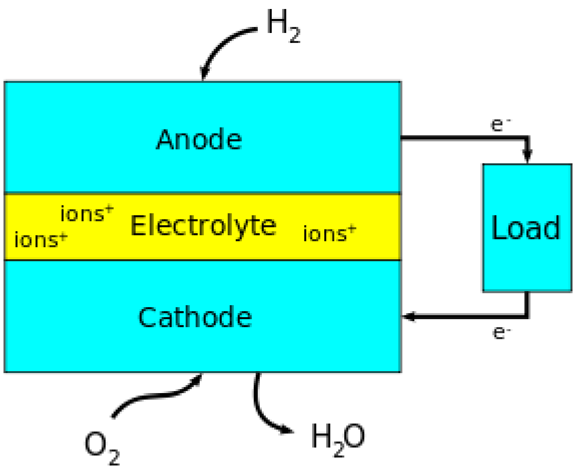


A block diagram of a fuel cell

Design features in a fuel cell include:

- The electrolyte substance, which usually defines the *type* of fuel cell, and can be made from a number of substances like potassium hydroxide, salt carbonates, and phosphoric acid.[19]
- The fuel that is used. The most common fuel is hydrogen.
- The anode catalyst, usually fine platinum powder, breaks down the fuel into electrons and ions.
- The cathode catalyst, often nickel, converts ions into waste chemicals, with water being the most common type of waste.[20]
- Gas diffusion layers that are designed to resist oxidization.[20]

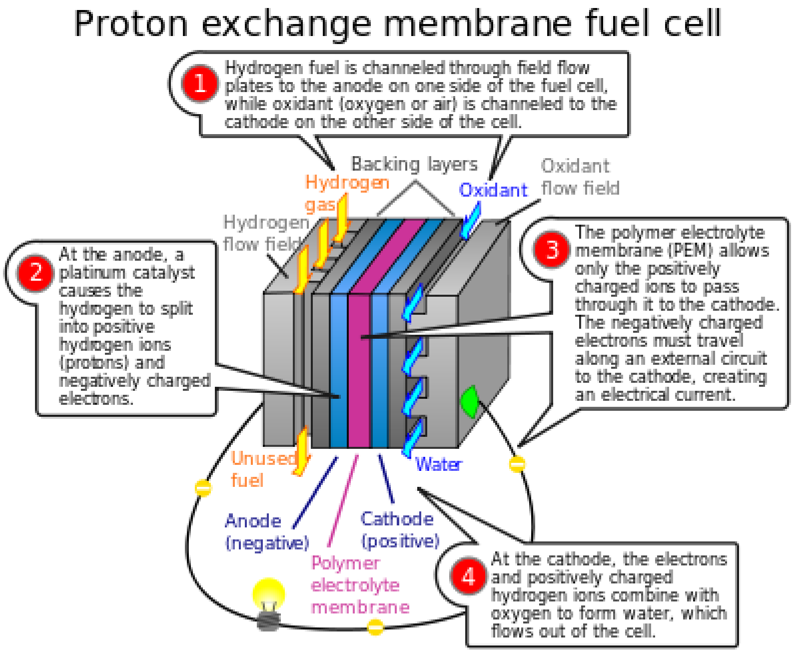
A typical fuel cell produces a voltage from 0.6–0.7 V at full rated load. Voltage decreases as current increases, due to several factors:

- Activation loss
- Ohmic loss (voltage drop due to resistance of the cell components and interconnections)
- Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage).[21]

To deliver the desired amount of energy, the fuel cells can be combined in series to yield higher voltage, and in parallel to allow a higher current to be supplied. Such a design is called a *fuel cell stack*. The cell surface area can also be increased, to allow higher current from each cell.

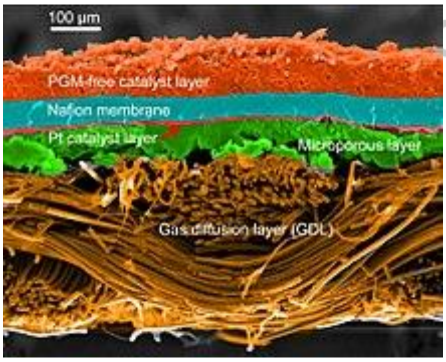
Proton-exchange membrane fuel cells (PEMFCs)[edit]

Main article: Proton-exchange membrane fuel cell



Construction of a high-temperature PEMFC: Bipolar plate as electrode with in-milled gas channel structure, fabricated from conductive composites (enhanced with graphite, carbon black, carbon fiber, and/or carbon nanotubes for more conductivity);[22] Porous carbon papers; reactive layer, usually on the polymer membrane applied; polymer membrane.

Condensation of water produced by a PEMFC on the air channel wall. The gold wire around the cell ensures the collection of electric current.[23]



SEM micrograph of a PEMFC MEA cross-section with a non-precious metal catalyst cathode and Pt/C anode.[24] False colors applied for clarity.

In the archetypical hydrogen–oxide proton-exchange membrane fuel cell design, a proton-conducting polymer membrane (typically nafion) contains the electrolyte solution that separates the anode and cathode sides.[25][26] This was called a *solid polymer electrolyte fuel cell* (*SPEFC*) in the early 1970s, before the proton exchange mechanism was well understood. (Notice that the synonyms *polymer electrolyte membrane* and '*proton exchange mechanism* result in the same acronym.)

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On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons. These protons often react with oxidants causing them to become what are commonly referred to as multi-facilitated proton membranes. The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water.

In addition to this pure hydrogen type, there are hydrocarbon fuels for fuel cells, including diesel, methanol (*see:* direct-methanol fuel cells and indirect methanol fuel cells) and chemical hydrides. The waste products with these types of fuel are carbon dioxide and water. When hydrogen is used, the CO_2 is released when methane from natural gas is combined with steam, in a process called steam methane reforming, to produce the hydrogen. This can take place in a different location to the fuel cell, potentially allowing the hydrogen fuel cell to be used indoors—for example, in fork lifts.

The different components of a PEMFC are

1. bipolar plates,
2. electrodes,
3. catalyst,
4. membrane, and
5. the necessary hardware such as current collectors and gaskets.[27]

The materials used for different parts of the fuel cells differ by type. The bipolar plates may be made of different types of materials, such as, metal, coated metal, graphite, flexible graphite, C–C composite, carbon–polymer composites etc.[28] The membrane electrode assembly (MEA) is referred as the heart of the PEMFC and is usually made of a proton exchange membrane sandwiched between two catalyst-coated carbon papers. Platinum and/or similar type of noble metals are usually used as the catalyst for PEMFC. The electrolyte could be a polymer membrane.

Proton-exchange membrane fuel cell design issues[edit]

Cost

In 2013, the Department of Energy estimated that 80-kW automotive fuel cell system costs of US$67 per kilowatt could be achieved, assuming volume production of 100,000 automotive units per year and US$55 per kilowatt could be achieved, assuming volume production of 500,000 units per year.[29] Many companies are working on techniques to reduce cost in a variety of ways including reducing the amount of platinum needed in each individual cell. Ballard Power Systems has experimented with a catalyst enhanced with carbon silk, which allows a 30% reduction (1.0–0.7 mg/cm²) in platinum usage without reduction in performance.[30] Monash University, Melbourne uses PEDOT as a cathode.[31] A 2011-published study[32] documented the first metal-free electrocatalyst using relatively inexpensive doped carbon nanotubes, which are less than 1% the cost of platinum and are of equal or superior performance. A recently published article demonstrated how the environmental burdens change when using carbon nanotubes as carbon substrate for platinum.[33]

Water and air management[34][35] (in PEMFCs)

In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack, creating a gas "short circuit" where hydrogen and oxygen combine directly, generating heat that will damage the fuel cell. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. Methods to manage water in cells are being developed like electroosmotic pumps focusing on flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently.

Temperature management

The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through thermal loading. This is particularly challenging as the $2H_2 + O_2 \rightarrow 2H_2O$ reaction is highly exothermic, so a large quantity of heat is generated within the fuel cell.

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Durability, service life, and special requirements for some type of cells

Stationary fuel cell applications typically require more than 40,000 hours of reliable operation at a temperature of −35 °C to 40 °C (−31 °F to 104 °F), while automotive fuel cells require a 5,000-hour lifespan (the equivalent of 240,000 km (150,000 mi)) under extreme temperatures. Current service life is 2,500 hours (about 75,000 miles).[36] Automotive engines must also be able to start reliably at −30 °C (−22 °F) and have a high power-to-volume ratio (typically 2.5 kW/L).

Limited carbon monoxide tolerance of some (non-PEDOT) cathodes

Phosphoric acid fuel cell (PAFC)[edit]

Main article: Phosphoric acid fuel cell

Phosphoric acid fuel cells (PAFC) were first designed and introduced in 1961 by G. V. Elmore and H. A. Tanner. In these cells phosphoric acid is used as a non-conductive electrolyte to pass positive hydrogen ions from the anode to the cathode. These cells commonly work in temperatures of 150 to 200 degrees Celsius. This high temperature will cause heat and energy loss if the heat is not removed and used properly. This heat can be used to produce steam for air conditioning systems or any other thermal energy consuming system.[37] Using this heat in cogeneration can enhance the efficiency of phosphoric acid fuel cells from 40–50% to about 80%.[37] Phosphoric acid, the electrolyte used in PAFCs, is a non-conductive liquid acid which forces electrons to travel from anode to cathode through an external electrical circuit. Since the hydrogen ion production rate on the anode is small, platinum is used as catalyst to increase this ionization rate. A key disadvantage of these cells is the use of an acidic electrolyte. This increases the corrosion or oxidation of components exposed to phosphoric acid.[38]

Solid acid fuel cell (SAFC)[edit]

Main article: Solid acid fuel cell

Solid acid fuel cells (SAFCs) are characterized by the use of a solid acid material as the electrolyte. At low temperatures, solid acids have an ordered molecular structure like most salts. At warmer temperatures (between 140–150 °C for $CsHSO_4$), some solid acids undergo a phase transition to become highly disordered "superprotonic" structures, which increases conductivity by several orders of magnitude. The first proof-of-concept SAFCs were developed in 2000 using cesium hydrogen sulfate ($CsHSO_4$).[39] Current SAFC systems use cesium dihydrogen phosphate (CsH_2PO_4) and have demonstrated lifetimes in the thousands of hours.[40]

Alkaline fuel cell (AFC)[edit]

Main articles: Alkaline fuel cell and Alkaline anion exchange membrane fuel cell

The alkaline fuel cell or hydrogen-oxygen fuel cell was designed and first demonstrated publicly by Francis Thomas Bacon in 1959. It was used as a primary source of electrical energy in the Apollo space program.[41] The cell consists of two porous carbon electrodes impregnated with a suitable catalyst such as Pt, Ag, CoO, etc. The space between the two electrodes is filled with a concentrated solution of KOH or NaOH which serves as an electrolyte. H_2 gas and O_2 gas are bubbled into the electrolyte through the porous carbon electrodes. Thus the overall reaction involves the combination of hydrogen gas and oxygen gas to form water. The cell runs continuously until the reactant's supply is exhausted. This type of cell operates efficiently in the temperature range 343–413 K and provides a potential of about 0.9 V.[42] AAEMFC is a type of AFC which employs a solid polymer electrolyte instead of aqueous potassium hydroxide (KOH) and it is superior to aqueous AFC.

High-temperature fuel cells[edit]

Solid oxide fuel cell[edit]

Main article: Solid oxide fuel cell

Solid oxide fuel cells (SOFCs) use a solid material, most commonly a ceramic material called yttria-stabilized zirconia (YSZ), as the electrolyte. Because SOFCs are made entirely of solid materials, they are not limited to the flat plane configuration of other types of fuel cells and are often designed as rolled tubes. They require high operating temperatures (800–1000 °C) and can be run on a variety of fuels including natural gas.[43]

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SOFCs are unique since in those, negatively charged oxygen ions travel from the cathode (positive side of the fuel cell) to the anode (negative side of the fuel cell) instead of positively charged hydrogen ions travelling from the anode to the cathode, as is the case in all other types of fuel cells. Oxygen gas is fed through the cathode, where it absorbs electrons to create oxygen ions. The oxygen ions then travel through the electrolyte to react with hydrogen gas at the anode. The reaction at the anode produces electricity and water as by-products. Carbon dioxide may also be a by-product depending on the fuel, but the carbon emissions from an SOFC system are less than those from a fossil fuel combustion plant.[44] The chemical reactions for the SOFC system can be expressed as follows:[45]

Anode reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$

Overall cell reaction: $2H_2 + O_2 \rightarrow 2H_2O$

SOFC systems can run on fuels other than pure hydrogen gas. However, since hydrogen is necessary for the reactions listed above, the fuel selected must contain hydrogen atoms. For the fuel cell to operate, the fuel must be converted into pure hydrogen gas. SOFCs are capable of internally reforming light hydrocarbons such as methane (natural gas),[46] propane and butane.[47] These fuel cells are at an early stage of development.[48]

Challenges exist in SOFC systems due to their high operating temperatures. One such challenge is the potential for carbon dust to build up on the anode, which slows down the internal reforming process. Research to address this "carbon coking" issue at the University of Pennsylvania has shown that the use of copper-based cermet (heat-resistant materials made of ceramic and metal) can reduce coking and the loss of performance.[49] Another disadvantage of SOFC systems is slow start-up time, making SOFCs less useful for mobile applications. Despite these disadvantages, a high operating temperature provides an advantage by removing the need for a precious metal catalyst like platinum, thereby reducing cost. Additionally, waste heat from SOFC systems may be captured and reused, increasing the theoretical overall efficiency to as high as 80–85%.[43]

The high operating temperature is largely due to the physical properties of the YSZ electrolyte. As temperature decreases, so does the ionic conductivity of YSZ. Therefore, to obtain optimum performance of the fuel cell, a high operating temperature is required. According to their website, Ceres Power, a UK SOFC fuel cell manufacturer, has developed a method of reducing the operating temperature of their SOFC system to 500–600 degrees Celsius. They replaced the commonly used YSZ electrolyte with a CGO (cerium gadolinium oxide) electrolyte. The lower operating temperature allows them to use stainless steel instead of ceramic as the cell substrate, which reduces cost and start-up time of the system.[50]

Molten-carbonate fuel cell (MCFC)[edit]

Main article: Molten carbonate fuel cell

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Molten carbonate fuel cells (MCFCs) require a high operating temperature, 650 °C (1,200 °F), similar to SOFCs. MCFCs use lithium potassium carbonate salt as an electrolyte, and this salt liquefies at high temperatures, allowing for the movement of charge within the cell – in this case, negative carbonate ions.[51]

Like SOFCs, MCFCs are capable of converting fossil fuel to a hydrogen-rich gas in the anode, eliminating the need to produce hydrogen externally. The reforming process creates CO 2 emissions. MCFC-compatible fuels include natural gas, biogas and gas produced from coal. The hydrogen in the gas reacts with carbonate ions from the electrolyte to produce water, carbon dioxide, electrons and small amounts of other chemicals. The electrons travel through an external circuit creating electricity and return to the cathode. There, oxygen from the air and carbon dioxide recycled from the anode react with the electrons to form carbonate ions that replenish the electrolyte, completing the circuit.[51] The chemical reactions for an MCFC system can be expressed as follows:[52]

Anode reaction: $CO_3^{2-} + H_2 \rightarrow H_2O + CO_2 + 2e^-$

Cathode reaction: $CO_2 + ½O_2 + 2e^- \rightarrow CO_3^{2-}$

Overall cell reaction: $H_2 + ½O_2 \rightarrow H_2O$

As with SOFCs, MCFC disadvantages include slow start-up times because of their high operating temperature. This makes MCFC systems not suitable for mobile applications, and this technology will most likely be used for stationary

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fuel cell purposes. The main challenge of MCFC technology is the cells' short life span. The high-temperature and carbonate electrolyte lead to corrosion of the anode and cathode. These factors accelerate the degradation of MCFC components, decreasing the durability and cell life. Researchers are addressing this problem by exploring corrosion-resistant materials for components as well as fuel cell designs that may increase cell life without decreasing performance.[43]

MCFCs hold several advantages over other fuel cell technologies, including their resistance to impurities. They are not prone to "carbon coking", which refers to carbon build-up on the anode that results in reduced performance by slowing down the internal fuel reforming process. Therefore, carbon-rich fuels like gases made from coal are compatible with the system. The United States Department of Energy claims that coal, itself, might even be a fuel option in the future, assuming the system can be made resistant to impurities such as sulfur and particulates that result from converting coal into hydrogen.[43] MCFCs also have relatively high efficiencies. They can reach a fuel-to-electricity efficiency of 50%, considerably higher than the 37–42% efficiency of a phosphoric acid fuel cell plant. Efficiencies can be as high as 65% when the fuel cell is paired with a turbine, and 85% if heat is captured and used in a combined heat and power (CHP) system.[51]

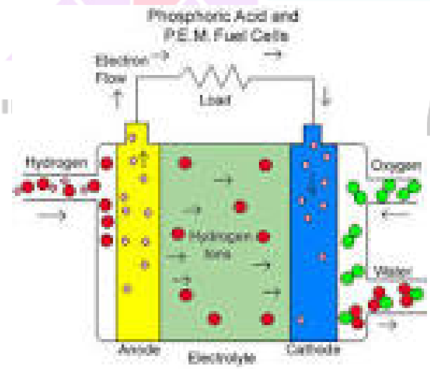
FuelCell Energy, a Connecticut-based fuel cell manufacturer, develops and sells MCFC fuel cells. The company says that their MCFC products range from 300 kW to 2.8 MW systems that achieve 47% electrical efficiency and can utilize CHP technology to obtain higher overall efficiencies. One product, the DFC-ERG, is combined with a gas turbine and, according to the company, it achieves an electrical efficiency of 65%.[53]

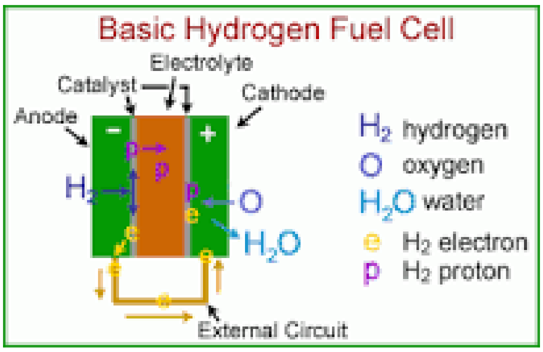
Electric storage fuel cell[edit]

The electric storage fuel cell is a conventional battery chargeable by electric power input, using the conventional electro-chemical effect. However, the battery further includes hydrogen (and oxygen) inputs for alternatively charging the battery chemically.

<u>How fuel cell works:</u>

A fuel cell works by passing hydrogen through the anode of a fuel cell and oxygen through the cathode. ... At the cathode, the protons, electrons, and oxygen combine to produce water molecules. Due to their high efficiency, fuel cells are very clean, with their only by-products being electricity, excess heat, and water.





Applications

Type 212 submarine with fuel cell propulsion of the German Navy in dry dock

Power

Stationary fuel cells are used for commercial, industrial and residential primary and backup power generation. Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, communications centers, rural locations including research stations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability.[74] This equates to less than one minute of downtime in a six-year period.[74]

Since fuel cell electrolyzer systems do not store fuel in themselves, but rather rely on external storage units, they can be successfully applied in large-scale energy storage, rural areas being one example.[75] There are many different types of stationary fuel cells so efficiencies vary, but most are between 40% and 60% energy efficient.[43] However, when the fuel cell's waste heat is used to heat a building in a cogeneration system this efficiency can increase to 85%.[43] This is significantly more efficient than traditional coal power plants, which are only about one third energy efficient.[76] Assuming production at scale, fuel cells could save 20–40% on energy costs when used in cogeneration systems.[77] Fuel cells are also much cleaner than traditional power generation; a fuel cell power plant using natural gas as a hydrogen source would create less than one ounce of pollution (other than CO_2) for every 1,000 kW·h produced, compared to 25 pounds of pollutants generated by conventional combustion systems.[78] Fuel Cells also produce 97% less nitrogen oxide emissions than conventional coal-fired power plants.

One such pilot program is operating on Stuart Island in Washington State. There the Stuart Island Energy Initiative[79] has built a complete, closed-loop system: Solar panels power an electrolyzer, which makes hydrogen. The hydrogen is stored in a 500-U.S.-gallon (1,900 L) tank at 200 pounds per square inch (1,400 kPa), and runs a ReliOn fuel cell to provide full electric back-up to the off-the-grid residence. Another closed system loop was unveiled in late 2011 in Hempstead, NY.[80]

Fuel cells can be used with low-quality gas from landfills or waste-water treatment plants to generate power and lower methane emissions. A 2.8 MW fuel cell plant in California is said to be the largest of the type.[81]

Cogeneration[edit]

Combined heat and power (CHP) fuel cell systems, including micro combined heat and power (MicroCHP) systems are used to generate both electricity and heat for homes (see home fuel cell), office building and factories. The system generates constant electric power (selling excess power back to the grid when it is not consumed), and at the same time produces hot air and water from the waste heat. As the result CHP systems have the potential to save primary energy as they can make use of waste heat which is generally rejected by thermal energy conversion systems.[82] A typical capacity range of home fuel cell is 1–3 kW_{el}, 4–8 kW_{th}.[83][84] CHP systems linked to absorption chillers use their waste heat for refrigeration.[85]

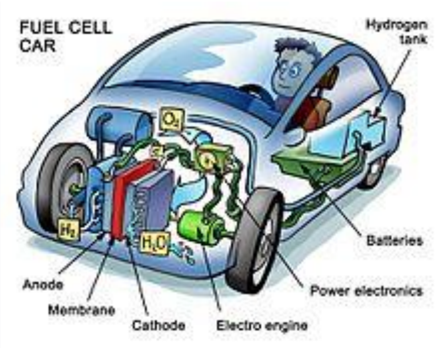
The waste heat from fuel cells can be diverted during the summer directly into the ground providing further cooling while the waste heat during winter can be pumped directly into the building. The University of Minnesota owns the patent rights to this type of system[86][87]

Co-generation systems can reach 85% efficiency (40–60% electric and the remainder as thermal).[43] Phosphoric-acid fuel cells (PAFC) comprise the largest segment of existing CHP products worldwide and can provide combined efficiencies close to 90%.[88][89] Molten carbonate (MCFC) and solid-oxide fuel cells (SOFC) are also used for combined heat and power generation and have electrical energy efficiencies around 60%.[90] Disadvantages of co-generation systems include slow ramping up and down rates, high cost and short lifetime.[91][92] Also their need to have a hot water storage tank to smooth out the thermal heat production was a serious disadvantage in the domestic market place where space in domestic properties is at a great premium.[93]

Delta-ee consultants stated in 2013 that with 64% of global sales the fuel cell micro-combined heat and power passed the conventional systems in sales in 2012.[73] The Japanese ENE FARM project will pass 100,000 FC mCHP systems in 2014, 34.213 PEMFC and 2.224 SOFC were installed in the period 2012–2014, 30,000 units on LNG and 6,000 on LPG.[94]

Fuel cell electric vehicles (FCEVs)[edit]

Main articles: Fuel cell vehicle, Hydrogen vehicle, and List of fuel cell vehicles



Configuration of components in a fuel cell car

Toyota Mirai

Element One fuel cell vehicle

Automobiles[edit]

As of 2017, about 6500 FCEVs have been leased or sold worldwide.[95] Three fuel cell electric vehicles have been introduced for commercial lease and sale: the Honda Clarity, Toyota Mirai and the Hyundai ix35 FCEV. Additional demonstration models include the Honda FCX Clarity, and Mercedes-Benz F-Cell.[96] As of June 2011 demonstration FCEVs had driven more than 4,800,000 km (3,000,000 mi), with more than 27,000 refuelling.[97] Fuel cell electric vehicles feature an average range of 314 miles between refuelling.[98] They can be refuelled in less than 5 minutes.[99] The U.S. Department of Energy's Fuel Cell Technology Program states that, as of 2011, fuel cells achieved 53–59% efficiency at one-quarter power and 42–53% vehicle efficiency at full power,[100] and a durability of over 120,000 km (75,000 mi) with less than 10% degradation.[101] In a Well-to-Wheels simulation analysis that "did not address the economics and market constraints", General Motors and its partners estimated that per mile travelled, a fuel cell electric vehicle running on compressed gaseous hydrogen produced from natural gas could use about 40% less energy and emit 45% less greenhouse gasses than an internal combustion vehicle.[102][103] A lead engineer from the Department of Energy whose team is testing fuel cell cars said in 2011 that the potential appeal is that "these are full-function vehicles with no limitations on range or refuelling rate so they are a direct replacement for any vehicle. For instance, if you drive a full sized SUV and pull a boat up into the mountains, you can do that with this technology and you can't with current battery-only vehicles, which are more geared toward city driving."[104]

In 2015, Toyota introduced its first fuel cell vehicle, the Mirai, at a price of $57,000.[105] Hyundai introduced the limited production Hyundai ix35 FCEV under a lease agreement.[106] In 2016, Honda started leasing the Honda Clarity Fuel Cell.[107]

Criticism[edit]

Some commentators believe that hydrogen fuel cell cars will never become economically competitive with other technologies[108][109][110] or that it will take decades for them to become profitable.[72][111] Elon Musk, CEO of battery-electric vehicle maker Tesla Motors, stated in 2015 that fuel cells for use in cars will never be commercially viable because of the inefficiency of producing, transporting and storing hydrogen and the flammability of the gas, among other reasons.[112] Jeremy P. Meyers estimated in 2008 that cost reductions over a production ramp-up period will take about 20 years after fuel-cell cars are introduced before they will be able to compete commercially with current market technologies, including gasoline internal combustion engines.[72] In 2011, the chairman and CEO of General Motors, Daniel Ackerson, stated that while the cost of hydrogen fuel cell cars is decreasing: "The car is still too expensive and probably won't be practical until the 2020-plus period, I don't know."[113]

In 2012, Lux Research, Inc. issued a report that stated: "The dream of a hydrogen economy ... is no nearer". It concluded that "Capital cost ... will limit adoption to a mere 5.9 GW" by 2030, providing "a nearly insurmountable barrier to adoption, except in niche applications". The analysis concluded that, by 2030, PEM stationary market will reach $1 billion, while the vehicle market, including forklifts, will reach a total of $2 billion.[111] Other analyses cite the lack of an extensive hydrogen infrastructure in the U.S. as an ongoing challenge to Fuel Cell Electric Vehicle commercialization. In 2006, a study for the IEEE showed that for hydrogen produced via electrolysis of water: "Only about 25% of the power generated from wind, water, or sun is converted to practical use." The study further noted that "Electricity obtained from hydrogen fuel cells appears to be four times as expensive as electricity drawn from the electrical transmission grid. ... Because of the high energy losses [hydrogen] cannot compete with electricity."[114] Furthermore, the study found: "Natural gas reforming is not a sustainable solution".[114] "The large amount of energy required to isolate hydrogen from natural compounds (water, natural gas, biomass), package the light gas by compression or liquefaction, transfer the energy carrier to the user, plus the energy lost when it is converted to useful electricity with fuel cells, leaves around 25% for practical use."[65][72][115]

In 2014, Joseph Romm, the author of *The Hype About Hydrogen* (2005), said that FCVs still had not overcome the high fueling cost, lack of fuel-delivery infrastructure, and pollution caused by producing hydrogen. "It would take several miracles to overcome all of those problems simultaneously in the coming decades."[116] He concluded that renewable energy cannot economically be used to make hydrogen for an FCV fleet "either now or in the future."[108] Greentech Media's analyst reached similar conclusions in 2014.[117] In 2015, *Clean Technica* listed some of the disadvantages of hydrogen fuel cell vehicles.[118] So did *Car Throttle*.[119] A 2019 video by *Real Engineering* noted that, notwithstanding the introduction of vehicles that run on hydrogen, using hydrogen as a fuel for cars does not help to reduce carbon emissions from transportation. The 95% of hydrogen still produced from fossil fuels releases carbon dioxide, and producing hydrogen from water is an energy-consuming process. Storing hydrogen requires more energy either to cool it down to the liquid state or to put it into tanks under high pressure, and delivering the hydrogen to fueling stations requires more energy and may release more carbon. The hydrogen needed to move a FCV a kilometer costs approximately 8 times as much as the electricity needed to move a BEV the same distance.[120]

Buses **[edit]**

Toyota FCHV-BUS at the Expo 2005.

As of August 2011, there were about 100 fuel cell buses running around the world, including in Whistler, Canada; San Francisco, United States; Hamburg, Germany; Shanghai, China; London, England; and São Paulo, Brazil.[121] Most of these were manufactured by UTC Power, Toyota, Ballard, Hydrogenics, and Proton Motor. UTC buses had driven more than 970,000 km (600,000 mi) by 2011.[122] Fuel cell buses have from 39% to 141% higher fuel economy than diesel buses and natural gas buses.[102][123]

As of 2019, the NREL is evaluating several current and planned fuel cell bus projects in the U.S.[124]

Forklifts **[edit]**

A fuel cell forklift (also called a fuel cell lift truck) is a fuel cell-powered industrial forklift truck used to lift and transport materials. In 2013 there were over 4,000 fuel cell forklifts used in material handling in the US,[125] of which 500 received funding from DOE (2012).[126][127] Fuel cell fleets are operated by various companies, including Sysco Foods, FedEx Freight, GENCO (at Wegmans, Coca-Cola, Kimberly Clark, and Whole Foods), and H-E-B Grocers.[128] Europe demonstrated 30 fuel cell forklifts with Hylift and extended it with HyLIFT-EUROPE to 200 units,[129] with other projects in France [130][131] and Austria.[132] Pike Research projected in 2011 that fuel cell-powered forklifts would be the largest driver of hydrogen fuel demand by 2020.[133]

Most companies in Europe and the US do not use petroleum-powered forklifts, as these vehicles work indoors where emissions must be controlled and instead use electric forklifts.[134][135] Fuel cell-powered forklifts can provide benefits over battery-powered forklifts as they can be refueled in 3 minutes and they can be used in refrigerated warehouses, where their performance is not degraded by lower temperatures. The FC units are often designed as drop-in replacements.[136][137]

Motorcycles and bicycles **[edit]**

In 2005 a British manufacturer of hydrogen-powered fuel cells, Intelligent Energy (IE), produced the first working hydrogen-run motorcycle called the ENV (Emission Neutral Vehicle). The motorcycle holds enough fuel to run for four hours, and to travel 160 km (100 mi) in an urban area, at a top speed of 80 km/h (50 mph).[138] In 2004 Honda developed a fuel-cell motorcycle that utilized the Honda FC Stack.[139][140]

Other examples of motorbikes[141] and bicycles[142] that use hydrogen fuel cells include the Taiwanese company APFCT's scooter[143] using the fueling system from Italy's Acta SpA[144] and the Suzuki Burgman scooter with an IE fuel cell that received EU Whole Vehicle Type Approval in 2011.[145] Suzuki Motor Corp. and IE have announced a joint venture to accelerate the commercialization of zero-emission vehicles.[146]

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Airplanes[edit]

In 2003, the world's first propeller-driven airplane to be powered entirely by a fuel cell was flown. The fuel cell was a stack design that allowed the fuel cell to be integrated with the plane's aerodynamic surfaces.[147] Fuel cell-powered unmanned aerial vehicles (UAV) include a Horizon fuel cell UAV that set the record distance flown for a small UAV in 2007.[148] Boeing researchers and industry partners throughout Europe conducted experimental flight tests in February 2008 of a manned airplane powered only by a fuel cell and lightweight batteries. The fuel cell demonstrator airplane, as it was called, used a proton exchange membrane (PEM) fuel cell/lithium-ion battery hybrid system to power an electric motor, which was coupled to a conventional propeller.[149]

In 2009 the Naval Research Laboratory's (NRL's) Ion Tiger utilized a hydrogen-powered fuel cell and flew for 23 hours and 17 minutes.[150] Fuel cells are also being tested and considered to provide auxiliary power in aircraft, replacing fossil fuel generators that were previously used to start the engines and power on board electrical needs, while reducing carbon emissions.[151][152][*failed verification*] In 2016 a Raptor E1 drone made a successful test flight using a fuel cell that was lighter than the lithium-ion battery it replaced. The flight lasted 10 minutes at an altitude of 80 metres (260 ft), although the fuel cell reportedly had enough fuel to fly for two hours. The fuel was contained in approximately 100 solid 1 square centimetre (0.16 sq in) pellets composed of a proprietary chemical within an unpressurized cartridge. The pellets are physically robust and operate at temperatures as warm as 50 °C (122 °F). The cell was from Arcola Energy.[153]

Lockheed Martin Skunk Works Stalker is an electric UAV powered by solid oxide fuel cell.[154]

Boats[edit]

The world's first certified fuel cell boat (HYDRA), in Leipzig/Germany

The world's first fuel-cell boat HYDRA used an AFC system with 6.5 kW net output. Iceland has committed to converting its vast fishing fleet to use fuel cells to provide auxiliary power by 2015 and, eventually, to provide primary power in its boats. Amsterdam recently introduced its first fuel cell-powered boat that ferries people around the city's canals.[155]

Submarines[edit]

The Type 212 submarines of the German and Italian navies use fuel cells to remain submerged for weeks without the need to surface.

The U212A is a non-nuclear submarine developed by German naval shipyard Howaldtswerke Deutsche Werft.[156] The system consists of nine PEM fuel cells, providing between 30 kW and 50 kW each. The ship is silent, giving it an advantage in the detection of other submarines.[157] A naval paper has theorized about the possibility of a nuclear-fuel cell hybrid whereby the fuel cell is used when silent operations are required and then replenished from the Nuclear reactor (and water).[158]

Portable power systems[edit]

Portable fuel cell systems are generally classified as weighing under 10 kg and providing power of less than 5 kW.[159] The potential market size for smaller fuel cells is quite large with an up to 40% per annum potential growth rate and a market size of around $10 billion, leading a great deal of research to be devoted to the development of portable power cells.[160] Within this market two groups have been identified. The first is the microfuel cell market, in the 1-50 W range for power smaller electronic devices. The second is the 1-5 kW range of generators for larger scale power generation (e.g. military outposts, remote oil fields).

Microfuel cells are primarily aimed at penetrating the market for phones and laptops. This can be primarily attributed to the advantageous energy density provided by fuel cells over a lithium-ion battery, for the entire system. For a battery, this system includes the charger as well as the battery itself. For the fuel cell this system would include the cell, the necessary fuel and peripheral attachments. Taking the full system into consideration, fuel cells have been shown to provide 530Wh/kg compared to 44 Wh/kg for lithium ion batteries.[160] However, while the weight of fuel cell systems offer a distinct advantage the current costs are not in their favor. while a battery system will generally cost around $1.20 per Wh, fuel cell systems cost around $5 per Wh, putting them at a significant disadvantage.[160]

As power demands for cell phones increase, fuel cells could become much more attractive options for larger power generation. The demand for longer on time on phones and computers is something often demanded by consumers so fuel cells could start to make strides into laptop and cell phone markets. The price will continue to go down as developments in fuel cells continues to accelerate. Current strategies for improving micro fuelcells is through the use of carbon nanotubes. It was shown by Girishkumar et al. that depositing nanotubes on electrode surfaces allows for substantially greater surface area increasing the oxygen reduction rate.[161]

Fuel cells for use in larger scale operations also show much promise. Portable power systems that use fuel cells can be used in the leisure sector (i.e. RVs, cabins, marine), the industrial sector (i.e. power for remote locations including gas/oil wellsites, communication towers, security, weather stations), and in the military sector. SFC Energy is a German manufacturer of direct methanol fuel cells for a variety of portable power systems.[162] Ensol Systems Inc. is an integrator of portable power systems, using the SFC Energy DMFC.[163] The key advantage of fuel cells in this market is the great power generation per weight. While fuel cells can be expensive, for remote locations that require dependable energy fuel cells hold great power. For a 72-h excursion the comparison in weight is substantial, with a fuel cell only weighing 15 pounds compared to 29 pounds of batteries needed for the same energy.[159]

Other applications[edit]

- Providing power for base stations or cell sites[164][165]
- Distributed generation
- Emergency power systems are a type of fuel cell system, which may include lighting, generators and other apparatus, to provide backup resources in a crisis or when regular systems fail. They find uses in a wide variety of settings from residential homes to hospitals, scientific laboratories, data centers,[166]
- telecommunication[167] equipment and modern naval ships.
- An uninterrupted power supply (*UPS*) provides emergency power and, depending on the topology, provide line regulation as well to connected equipment by supplying power from a separate source when utility power is not available. Unlike a standby generator, it can provide instant protection from a momentary power interruption.
- Base load power plants
- Solar Hydrogen Fuel Cell Water Heating
- Hybrid vehicles, pairing the fuel cell with either an ICE or a battery.
- Notebook computers for applications where AC charging may not be readily available.
- Portable charging docks for small electronics (e.g. a belt clip that charges a cell phone or PDA).
- Smartphones, laptops and tablets.
- Small heating appliances[168]
- Food preservation, achieved by exhausting the oxygen and automatically maintaining oxygen exhaustion in a shipping container, containing, for example, fresh fish.[169]
- Breathalyzers, where the amount of voltage generated by a fuel cell is used to determine the concentration of fuel (alcohol) in the sample.[170]
- Carbon monoxide detector, electrochemical sensor.

Fueling stations[edit]

Main articles: Hydrogen station and Hydrogen highway

Hydrogen fueling station.

In 2013, *The New York Times* reported that there were "10 hydrogen stations available to the public in the entire United States: one in Columbia, S.C., eight in Southern California and the one in Emeryville".[171] As of December 2016, there were 31 publicly accessible hydrogen refueling stations in the US, 28 of which were located in California.[172]

A public hydrogen refueling station in Iceland operated from 2003 to 2007. It served three buses in the public transport net of Reykjavík. The station produced its own hydrogen with an electrolyzing unit.[173] The 14 stations in Germany were planned to be expanded to 50 by 2015[174] through its public–private partnership Now GMBH.[175]

By May 2017, there were 91 hydrogen fueling stations in Japan.[176] As of 2016, Norway planned to build a network of hydrogen stations between the major cities, starting in 2017.[177]

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