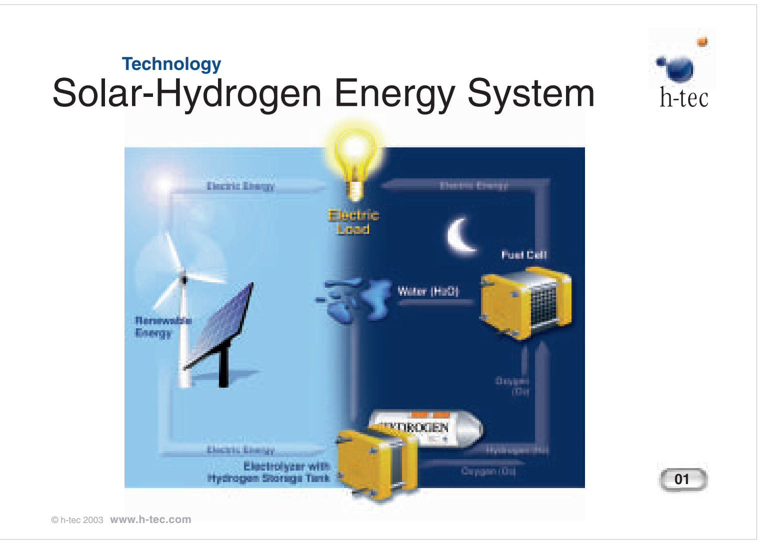

Technology

Solar-Hydrogen Energy System

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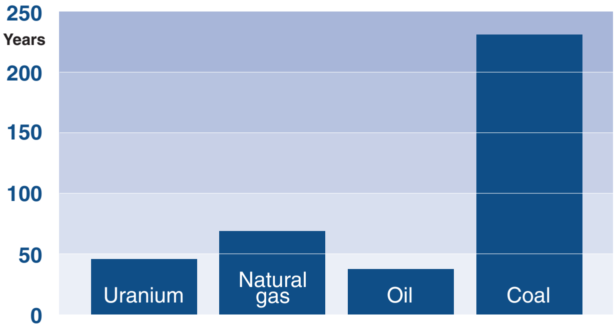
Solar-Hydrogen Energy Cycle

Diminishing resources, more severe environmental pollution and an ever-increasing demand for energy force us to reconsider the structure of our energy supply system.

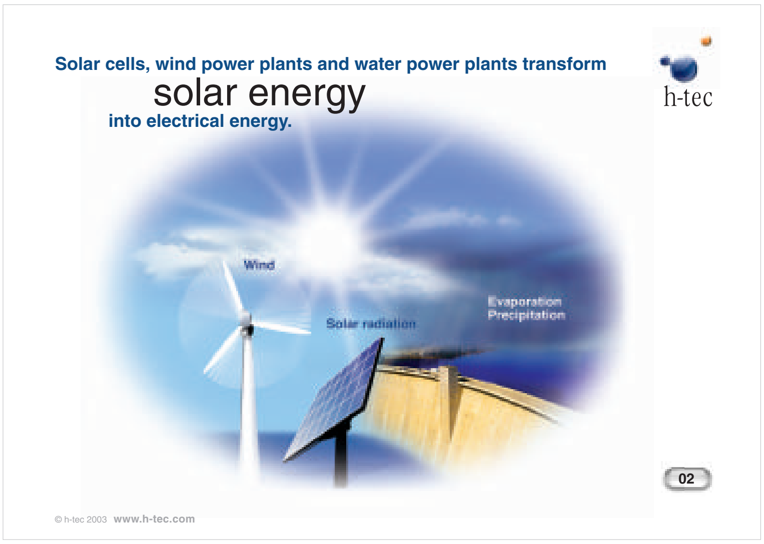
Our global resources of fossil and nuclear fuels are limited.



Projected availability of fossil and nuclear fuels (based on today's rate of consumption).
Source: L-B-Systemtechnik, www.energiekrise.de

The necessary changes in our energy supply system can be accomplished if we are able to establish regenerative energies like solar, wind and hydroelectric energy as a fundamental part of the energy market.

One issue we are faced with when we use solar panels or wind power plants to produce electricity is that energy supply and demand often do not coincide. For example, a solar panel will provide electricity during the day but we might want to use electricity to power a light in the evening. Or, we might want to use wind-generated electricity in a place far away from the power plant. Hence, when supply and demand do not coincide we need a convenient way to both store and transport regenerative energy. This is where hydrogen comes into play, as a future storage and transport medium for energy. The combination of solar energy for electricity production and hydrogen for energy transport and storage is called the solar-hydrogen energy cycle. During times when solar panels and wind power plants supply more energy than needed the excess energy is used to produce hydrogen (bottom path on the transparency). This is accomplished with electrolyzers that use electricity to split water into oxygen and hydrogen. The hydrogen (and potentially the oxygen) can be stored and transported as necessary. When we need electricity the gas(es) are fed into a fuel cell which converts the chemical energy of the hydrogen (and oxygen) into electricity, water and heat. In this way our energy demands can be met anywhere and anytime.


Solar cells, wind power plants and water power plants transform
solar energy
into electrical energy.

Solar Energy

Renewable energies: what they are and how we can use them.

Renewable energies have energy sources that are continuously being replenished by natural processes that occur on human timescales. In contrast, fossil fuels (coal, natural gas, oil) require millions of years of geological processes to form. Our resources of fossil and nuclear fuels (e.g. uranium) are limited. Regenerative energies, on the other hand, are virtually inexhaustible.

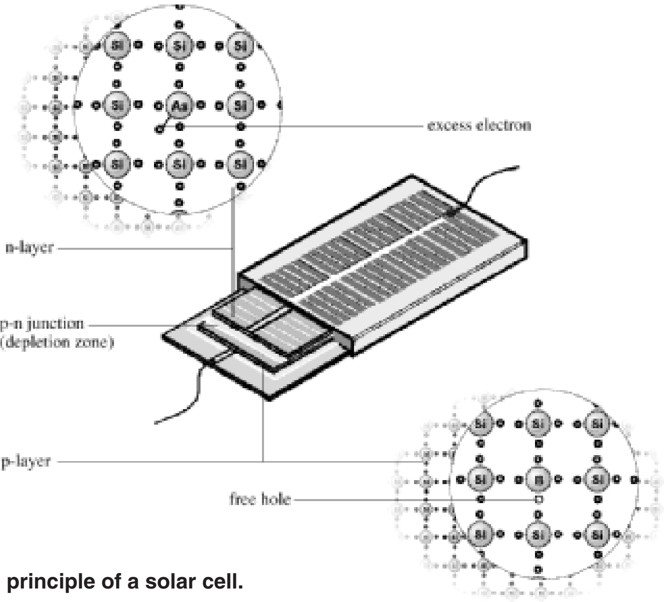
Examples of renewable energy sources include:

Solar energy (hydrogen fusion in the Sun)
Solar energy surrounds us in different forms and can be used in a variety of ways, including:
- Solar radiation: photovoltaics, solar heat
- Atmospheric movement: wind energy
- Evaporation/precipitation:
  hydroelectric energy/water power
- Biomass: e.g., fibre fuel, biogas

Today's most widespread applications for using regenerative energies are solar panels, wind power plants and hydroelectric power plants.

Tidal energy (gravitational attraction of Sun, Earth and Moon)
Tidal power plants use the energy provided by high and low tides. Water is stored during high tide and released during low tide, powering turbines in the process.

Geothermal energy (radioactivity in Earth's interior, plate tectonics)
Geothermal power plants use heat released from the interior through Earth's crust.



Basic principle of a solar cell.
Source: h-tec GmbH, www.h-tec.com

Photovoltaic

Photovoltaic systems convert sunlight directly into electrical energy.

The backbone of this technology are semiconducting materials such as silicon.

A typical solar cell consists of two differently doped semiconductors. Doping is the controlled introduction of impurities into the host material. Starting out with a pure semiconductor crystal (say, silicon) this is achieved by substituting some of the atoms in the crystal lattice with elements that have one more or one less valence electron than the host material (Valence electrons are the electrons that determine the chemical behavior of a material, they are located in the outermost orbital shell of the atom).
Semiconducting elements have four valence electrons all of which are used for bonding in the crystal lattice. If the doping material has five valence electrons there will be one additional, loosely bound electron per dopant atom. These 'free' atoms can move about easily in the lattice and are responsible for an increase in conductivity. Since they have a negative charge the material doped in this way is called an n-type semiconductor. If, on the other hand, the doping material has only three valence electrons the lattice structure will be deficient of electrons and there will be one hole, or positive charge, per dopant atom. Similar to the free electrons above the holes can easily move about in the lattice, again causing an increase in conductivity. Since in this case the free charge carriers are positive this kind of semiconductor is said to be of p-type.

When a p-type semiconductor is joined to an n-type semiconductor, a p-n junction is created. While each side by itself is electrically neutral (there are as many electrons as there are protons) this different for certain areas of the combined configuration. The concentration differences of holes and free electrons between the n- and p-regions produce a diffusion current: electrons flow from the n-side and fill holes on the p-side. This creates a region that is almost devoid of free charge carriers (i.e. free electrons or holes) and is therefore called the depletion zone. In the depletion zone there is a net positive charge on the n-side and a net negative charge on the p-side resulting in an electric field that opposes a further flow of electrons. The more electrons move from the n- to the p-side the stronger the opposing field will be and eventually an equilibrium will be reached in which no further electrons are able to move against the electric field. The potential difference of the equilibrium electric field is called the diffusion voltage. It cannot be used externally.

However, when light hits the solar cell the equilibrium conditions are disturbed and the so-called inner photo effect creates additional charge carriers that are free to move in the electric field of the depletion zone.
Holes move towards the p-region and electrons towards the n-region, thus creating an external voltage (no-load voltage) at the cell. The no-load voltage of a solar cell is material dependent and does not depend on the cell's surface area. A silicon solar cell has a no-load voltage of about 0.5V. Higher voltages can be obtained by connecting individual cells in series.

The current delivered by a solar cell is proportional to the intensity of the incoming light. Higher currents can be achieved by connecting cells in parallel.

The power of a solar cell depends on the connected electrical load. The maximum power point (MPP) can easily be determined from the power-voltage characteristic of the cell.

The efficiency of a solar cell is temperature dependent. It will decrease with increasing temperature.

The most common semiconductor material used in solar cells is silicon. A number of different degrees in lattice alignment are in use:

- monocrystalline silicon
(cell efficiency of approx. 15 - 18 %)

- polycrystalline silicon
(cell efficiency of approx. 12 - 14 %)

- amorphic silicon
(cell efficiency of approx. 5 - 8 %)

Wind energy

Wind energy has been used for centuries. Windmills converted wind energy into mechanical energy which was used to perform tasks such as crushing grains to make flour. Today wind energy is used by wind power plants to generate electricity.

The most important components of a wind power system are:

Foundation - ensures that the system has sufficient anchoring.

Mast- typically made of steel or concrete, at present between 10 and 100 m high; even higher ones are planned in the future.

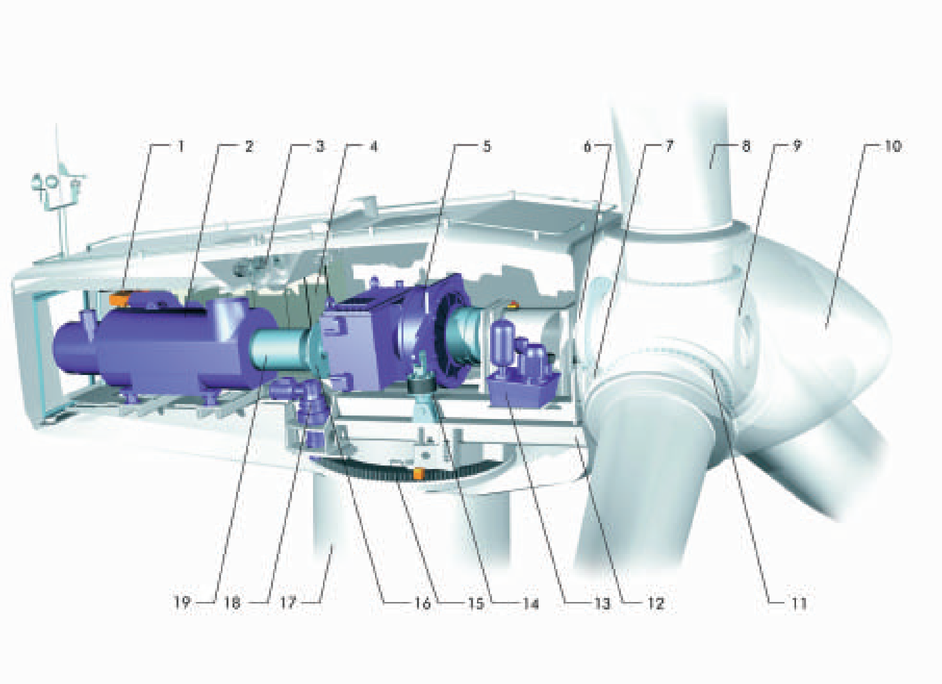
Gondola - provides the framework for generator, transmission and other components.

Rotor - converts wind energy with one or more rotor blades into rotational mechanical energy. The rotor shaft connects rotor and transmission.

Transmission/gear - translates the rotor's low rotation rate into the higher rotation rate required to operate the generator. Some wind energy systems no longer require a transmission between rotor and generator.

Generator - converts mechanical into electrical energy

Commercial wind power plants have total efficiencies of between 35 % and 43 %. The greatest energy loss occurs at the rotor (aerodynamic loss) which transfers only about 45 - 50 % of the wind energy into mechanical energy. Losses associated with the transmission (frictional) and generator (electrical) are 2.5 % and ~ 5 %, respectively.



Wind power plant

Diagram of a typical wind power plant

Source: Vestas, www.vestas.de

1. Service crane
2. OptiSpeed™-generator
3. Cooling system
4. VMP-top controller with converter
5. Gearbox
6. Main shaft
7. Rotor lock system
8. Blade
9. Blade hub
10. Spinner
11. Blade bearing
12. Machine foundation
13. Hydraulic unit
14. Gear torque arm
15. Yaw ring
16. Brake
17. Tower
18. Yaw gear
19. Composite disc coupling

Water power

Hydroelectric power plants convert the kinetic energy of moving water into electrical energy. A typical scenario is a hydroelectric power plant installed in combination with a river dam. The dam raises the water level in the reservoir.

As water from the reservoir is allowed to fall through pipes, its potential energy is converted into kinetic energy which in turn is used to power a turbine. The turbine converts the kinetic energy into mechanical energy. A generator finally converts the mechanical into electrical energy.

Hydroelectric power plants reach efficiencies of up to 80 - 90 %.

The power P of the system is given by:

$$P = \frac{\Delta V}{\Delta t} \times \Delta h \times g \times \rho \times \eta$$

where $\Delta V/\Delta t$	water flux (volume per time)
Δh	height at fall
g	gravitational acceleration (9.81 m/s^2)
ρ	density of water
η	total efficiency of the system

Alternatively, they can be classified into run-of-river and storage power plants.

Run-of-river power plants are used at rivers with small height of fall and large flux. They operate continuously and are therfore suitable base load power stations.
In storage power plants water is stored in natural or artificial reservoirs. This allows to control flow irregularities as well as to adjust the electricity production to the energy demand. Water can be released from the reservoir during peak times when energy demands are highest. Storage power stations are therefore particularly suitable as peak load power stations.

Pump storage power stations are a special case of storage power stations. During times of low electricity demand (for example, at night) excess electricity from base load power stations is used to pump water into a reservoir. During peak times the water is released again and used to generate electricity. Pump storage power plants have efficiencies of up to 75 %.

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Different ways to
store hydrogen

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Pressure storage tank
Source: Dynetek

Cryogenic storage tank
Source: Linde AG

Metal hydride storage tank
Source: HERA
Hydrogen Storage Systems

03

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Hydrogen Storage

Hydrogen can be stored in various ways, e.g. as a pressurized gas, as a cryogenic liquid as a metal hydride or in a carbon nanofiber structure.

Pressure storage

The easiest and most economical method of storing hydrogen is to simply compress the gas and store it in containers that can withstand the resulting high pressure. Unless space or weight are issues this is the storage method of choice. Conventional pressure tanks are designed to withstand pressures of up to 200 bar and can therefore hold 200 times the volume of a given gas (as compared to the gas volume at ambient pressures). They are mainly used for indoor and stationary applications.
Among the more recent developments in this area are tanks made of carbon composites. Not only are these more lightweight than their conventional counterparts but they can also withstand pressures of up to 350 bar (700 bar in the future).

Cryogenic storage (liquid hydrogen storage)

In this method hydrogen is stored as a liquid at temperatures below - 253° C. The major advantage is the high energy storage density per volume (and mass), i.e. a given volume of liquid hydrogen contains many times the energy of the same volume of hydrogen gas. This is particularly important when there is limited space (e.g. during transport on tankers).

Hydrogen changes into its liquid phase at a temperature of - 253° C. At temperatures this low it can only be stored in special cryogenic storage tanks that are sufficiently well insulated. But even in these tanks the liquid hydrogen can be stored without losses for only a few days. After that, there will be evaporation losses, despite the insulation. These occur when - due to a slight temperature increase - a small portion of the hydrogen evaporates and thus returns to the gas phase. To avoid the build-up of high pressures in the tank the gaseous hydrogen has to be released. The losses due to this process amount to about 0.4 % of the tank volume per day.
Another significant loss is associated with the liquefaction process: the energy required to liquefy the hydrogen amounts to approximately one third of the total energy stored.

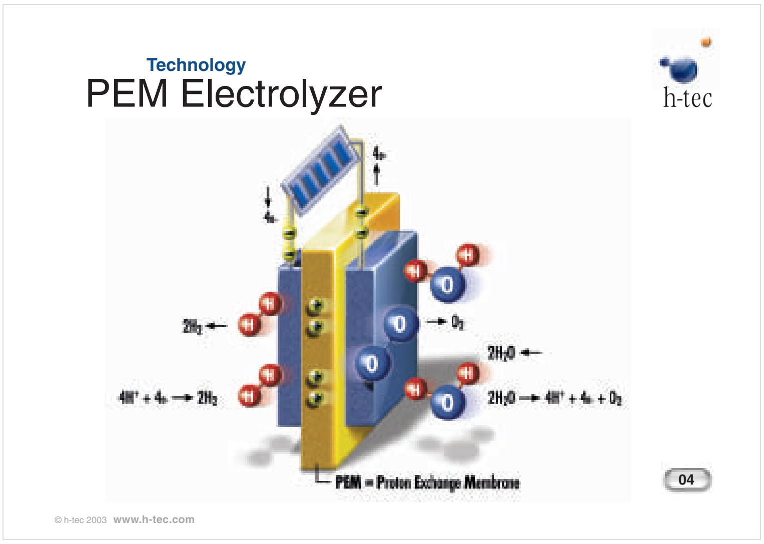
Metal hydride storage

Hydrogen can be stored as a metal hydride, in the crystal lattice of certain metals or metal alloys. At pressures slightly exceeding the ambient pressure the hydrogen is pumped into the storage medium where it bonds to the metal (metal alloy) to form a metal hydride, releasing heat in the process (exothermic reaction). The reaction is reversible: by applying heat the hydrogen can again be released from the tank for use in, for example, a fuel cell.

Compared to the methods above hydrogen that is stored as a metal hydride is safer and easier to handle. Metal hydride storage has a high energy storage density per volume. This could make it suitable for use in automobiles as enough fuel can be stored in a small volume to provide a sufficient range for the vehicle. However, there is one major issue: the energy storage density per mass is low and, consequently, metal hydride storage tanks are heavy. This continues to be a problem for its widespread use in automobiles.

Carbon nanofiber storage

In this method hydrogen is stored in carbon nanofiber structures. Carbon nanofiber technology - while still at the basic research state - shows a lot of promise for the future as the tank material would have both high energy storage density per volume and mass, making it a viable option for use in automobiles.



Technology

PEM Electrolyzer

h-tec

04

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PEM Electrolyzer

Hydrogen and oxygen can be produced by the electrolysis of water. Electrolysis is an electrochemical process through which a substance (the electrolyte) is decomposed when an external DC voltage is applied to two electrodes (cathode and anode) that are in contact with the electrolyte. For electrolysis to happen the DC voltage must be equal to or exceed a certain material-dependent threshold voltage known as the decomposition voltage. Different types of electrolyzers are usually distinguished by their type of electrolyte and/or electrodes.

PEM* electrolyzers have a particularly simple and compact design. The central component is a proton-conducting polymer membrane which is coated with a layer of catalyst material on either side. These two layers are the electrodes of the cell.

When a DC voltage greater than the decomposition voltage of water is applied to its electrodes, the PEM electrolyzer splits pure water into hydrogen and oxygen. The theoretical decomposition voltage of water is 1.23 V, however, because of transition resistances, somewhat higher voltages are necessary in practice.

Higher power electrolyzers are built as stacks in which individual electrolyzers are connected in series and voltages are added.

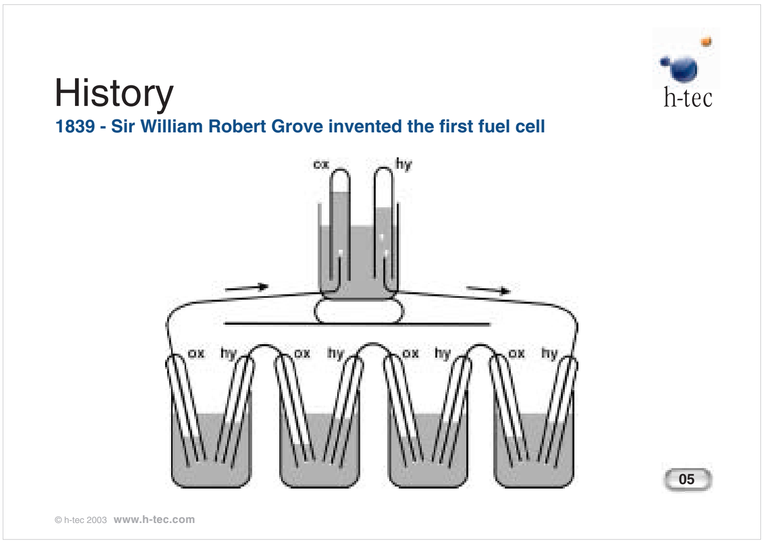
PEM electrolyzers have efficiencies of up to ~ 85 %.

How PEM electrolyzers work
Suppose a DC voltage is applied to the PEM electrolyzer electrodes (solar panel on the transparency). At the anode (electrode on the right) water is oxidized, leaving oxygen, protons (H^+-ions) and free electrons. While the oxygen gas can be collected directly at the anode, the protons (yellow +) migrate through the proton-conducting membrane to the cathode where they are reduced to hydrogen (the electrons for this are provided by the external circuit).

Cathode reaction: $4H^+ + 4e^- \text{ –> } 2H_2$
Anode reaction: $2H_2O \text{ –> } 4H^+ + 4e^- + O_2$

Cathode reaction: $4H^+ + 4e^- \text{ –> } 2H_2$

**PEM electrolyzers are named after their electrolyte material, a proton-conducting polymer membrane. The acronym PEM stands for proton exchange-membrane or polymer-electrolyte-membrane. A PEM consists of a teflon-like polymer structure to which sulfonic acid groups (SOH$_3$) are attached. When the membrane becomes wet the sulfonic acid dissociates, the membrane becomes acidic and thereby proton-conducting. While this allows for an easy transport of protons (H^+-ions), anions (negatively charged ions) cannot pass the membrane.*



History

1839 - Sir William Robert Grove invented the first fuel cell

05

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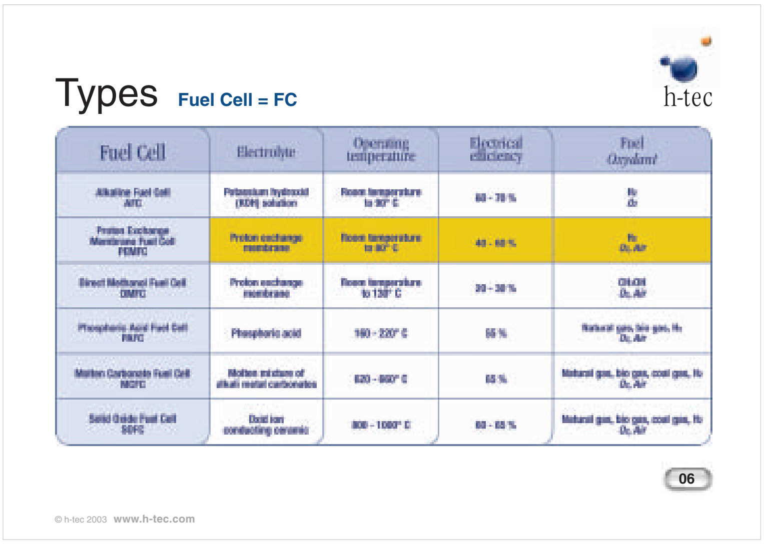
History of Fuel Cell Technology

The fuel cell was invented more than 150 years ago; in 1839 Sir William Robert Grove (1811 - 1896) and Christian Friedrich Schoenbein (1799 - 1868) discovered that the electrolysis process can be reversed.

For example, in the electrolysis of water, electricity is used to produce hydrogen and oxygen. In a fuel cell the reverse reaction occurs: hydrogen and oxygen react to form water and electricity is produced.

Grove developed his first fuel cell in 1839. The diagram in the figure above shows a model built in 1842 consisting of four elements that are connected in series. Each of the four containers is filled with diluted sulfuric acid and has two glass tubes with platinum electrodes on the inside. In the top portion of the glass tubes hydrogen surrounds the anodes and oxygen the cathodes. The electricity generated can be tapped into externally: in the diagram it is used to operate an electrolyzer.

Difficulties with materials, the invention of the combustion and electric engine and a seemingly inexhaustible abundance of fossil fuels are among the reasons why fuel cell technology remained insignificant as a means to generate electricity for over a century. It was only in the 1960s that it was rediscovered for use in space exploration where it was needed to provide reliable, combustion-free energy. The basic research done in period was the crucial impulse for the develepment fuel cell technology.



Types **Fuel Cell = FC**

Fuel Cell	Electrolyte	Operating temperature	Electrical efficiency	Fuel Oxydant
Alkaline Fuel Cell AFC	Potassium hydroxid (KOH) solution	Room temperature to 90° C	60 - 70 %	H_2 O_2
Proton Exchange Membrane Fuel Cell PEMFC	Proton exchange membrane	Room temperature to 80° C	40 - 60 %	H_2 O_2, Air
Direct Methanol Fuel Cell DMFC	Proton exchange membrane	Room temperature to 130° C	20 - 30 %	CH_3OH O_2, Air
Phosphoric Acid Fuel Cell PAFC	Phosphoric acid	160 - 220° C	55 %	Natural gas, bio gas, H_2 O_2, Air
Molten Carbonate Fuel Cell MCFC	Molten mixture of alkali metal carbonates	620 - 660° C	65 %	Natural gas, bio gas, coal gas, H_2 O_2, Air
Solid Oxide Fuel Cell SOFC	Oxid ion conducting ceramic	800 - 1000° C	60 - 65 %	Natural gas, bio gas, coal gas, H_2 O_2, Air

06

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Types of Fuel Cells

A fuel cell essentially consists of two electrodes (cathode and anode) separated by an electrolyte. Usually the type of electrolyte is used to distinguish between different types of fuel cells. However, there are a number of additional characteristics such as operating temperature, efficiency and application which can vary significantly between different fuel cell types.

Alkaline Fuel Cell (AFC)

The electrolyte in an Alkaline Fuel Cell is caustic potash solution (KOH). Operating temperatures range from room temperature to ~ 90˚ C (but can be higher depending on electrolyte concentration). AFCs have excellent efficiencies and make use of inexpensive catalysts. The major challenge with AFCs is their incompatibility with carbon dioxide. CO_2 reacts with the electrolyte and forms and insoluble carbonate. This means that AFCs can only be operated with fuels that are extremely pure (highly pure hydrogen and oxygen), but not with air which contains CO_2.
Applications: military, space exploration

Cathode reaction: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Anode reaction: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$

Proton Exchange Membrane Fuel Cell (PEMFC)

The electrolyte in a Proton Exchange Membrane Fuel Cell is a proton-conducting polymer membrane. PEMFCs also operate at low temperatures (room temperature to ~ 80˚ C). They have an excellent cold-start performance and high efficiencies. Moreover, individual cells can easily be stacked (fuel cell stacks) which allows for higher output voltages and makes this type of electrolyzer highly adaptable to a wide variety of applications. The cathode is supplied with oxygen (e.g., from the air) while the anode receives hydrogen. If the hydrogen used was made from carbon-based fuels it must be ensured that the gas no longer contains any carbon monoxide (CO) as this will destroy the PEMFC catalyst. One drawback of PEM fuel cells is the high cost of their catalyst material (platinum).
Applications: Electric motors, e.g. in automobiles, space exploration, mobile electricity supply, battery substitute, block-type thermal power station (electricity-heat-coupling)

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

Direct Methanol Fuel Cell (DMFC)

The Direct Methanol Fuel Cell is a special case of the PEMFC. Both fuel cells have similar structures, however, the DMFC uses methanol (CH_3OH) as fuel, not hydrogen. This has the advantage that methanol can be used as a liquid. On the other hand, methanol is poisonous and corrosive and DMFCs have low efficiencies.
Applications: electric motors, portable electricity supply, battery substitute

Cathode reaction:
$3O_2 + 12H^+ + 12e^- \rightarrow 6H_2O$

Anode reaction:
$2CH_3OH + 2H_2O \rightarrow 2CO_2 + 12H^+ + 12e^-$

Phosporic Acid Fuel Cell (PAFC)

The electrolyte in a PAFC is phosphoric acid (H_3PO_4). Operating temperatures range between 160 - 220° C. Compared to other types of fuel cells (except DMFCs), PAFCs have low efficiencies.
Applications: stationary electricity supply, block-type thermal power stations (electricity-heat coupling)

Cathode reaction:
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Anode reaction:
$2H_2 \rightarrow 4H^+ + 4e^-$

Molten Carbonate Fuel Cell (MCFC)

The electrolyte in an MCFC is a molten alkali carbonate that is retained in a ceramic matrix of lithium aluminum oxide. MCFCs have high operating temperatures (600 - 700° C) and high efficiencies. They can be operated not only with hydrogen but also with other gases including natural gas and biogas.
Applications: block-type thermal power stations (electricity-heat coupling), utility power plants

Cathode reaction:
$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$

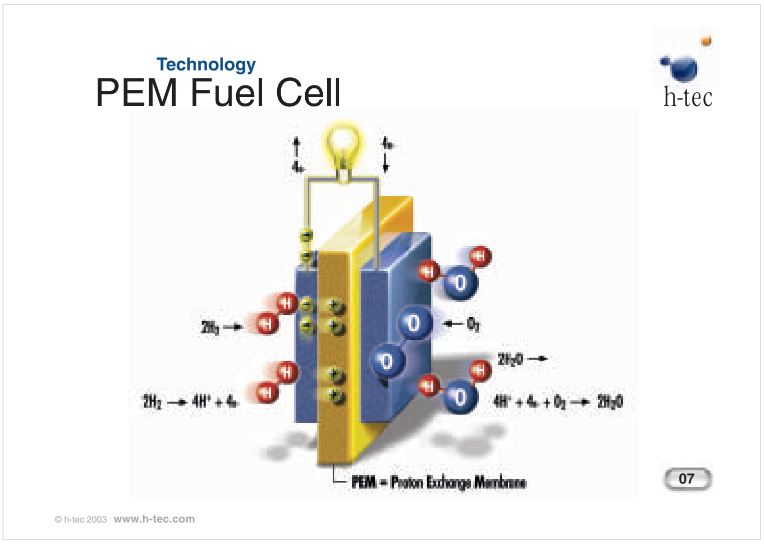
Anode reaction:
$2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$

Solid Oxide Fuel Cell (SOFC)

The electrolyte in this fuel cell is a solid metal oxide, usually yttrium-stabilized zirconium oxide (ZrO_2). SOFCs are high-temperature fuel cells. They can be operated with hydrogen but also other gases including natural gas and biogas.
Applications: block-type thermal power stations (electricity-heat coupling), utility power plants and also home electricity generation

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

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



Technology

PEM Fuel Cell

07

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PEM Fuel Cell

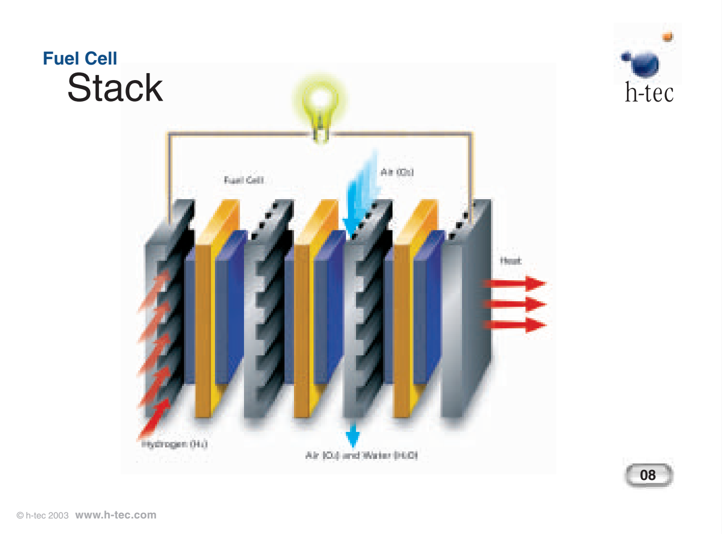
A PEM fuel cell directly converts chemical into electrical energy, at low operating temperatures, efficiently, quietly and virtually free of emissions (the only byproduct is water). In addition to their excellent cold-start performance and high efficiency, individual PEM fuel cells can easily be joined together to form a so-called fuel cell stack. By connecting cells in series appreciable output voltages can be achieved and highly different power requirements (from a few watts to several megawatts) can be met. With these characteristics PEMFCs are suitable for a wide range of applications, including electric motors in automobiles, space exploration, mobile electricity supply, battery substitution and block-type thermal power stations (electricity-heat coupling).

How a PEM fuel cell works

In a PEM fuel cell two electrodes (typically platinum, blue on the transparency) are separated by a proton-conducting polymer membrane, the electrolyte (yellow). Hydrogen gas (in red, left side) is supplied to one electrode and oxygen gas (in blue, right side) to the other. The anode is a catalyst for the dissociation of hydrogen into protons (H^+-ions) and electrons (yellow + and -). Both protons and electrons now travel to the cathode side (on the right) but - very importantly - on different paths. While the H^+-ions pass through the cell's proton-conducting membrane the electrons move through the (closed) external circuit and thereby provide the fuel cell's electric power (indicated by light bulb). At the cathode the protons and electrons finally react with the oxygen to form water (in red and blue), the fuel cell's only byproduct.

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

** PEM electrolyzers are named after their electrolyte material, a proton-conducting polymer membrane. The acronym PEM stands for proton-exchange-membrane or polymer-electrolyte-membrane. A PEM consists of a teflon-like polymer structure to which sulfonic acid groups (SOH_3) are attached. When the membrane becomes wet the sulfonic acid dissociates, the membrane becomes acidic and thereby proton-conducting. While this allows for an easy transport of protons (H^+-ions), anions (negatively charged ions) cannot pass the membrane.*

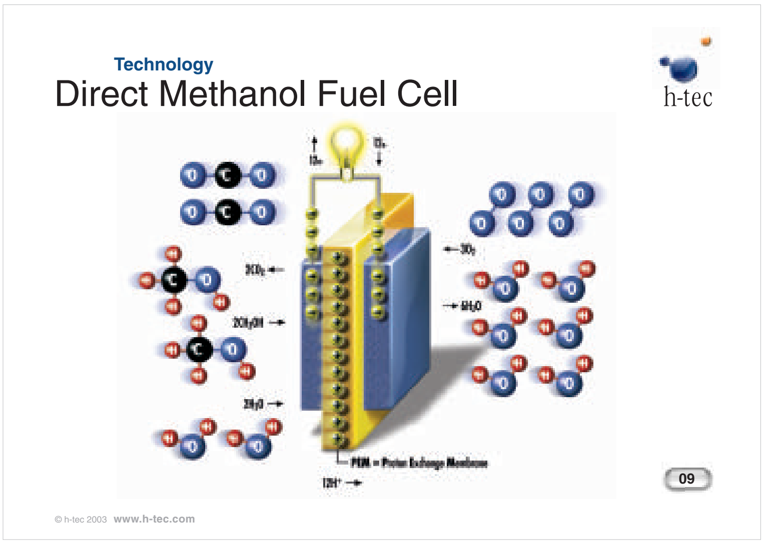


Fuel Cell Stack

In order to achieve appreciable output voltages several individual fuel cells must be combined to a unit called a fuel cell stack.

The diagram on the transparency shows a fuel cell stack consisting of three individual fuel cells. These are represented as yellow and blue units where the electrolyte (or PEM) is shown in yellow and the electrodes in blue. Adjacent cells are connected by a separator plate (grey with horizontal and vertical grooves) which has a number of tasks: 1) to provide the electrical connections between the cells, 2) to facilitate gas transport to and away from the cells, 3) to dissipate the heat produced in the cells, and 4) to seal off adjacent cells and prevent fuel and oxidant leakage. In the figure the electrical connections are not shown explicitly, the gas transport channels are represented by horizontal (hydrogen) and vertical (oxygen supply and water exhaust) grooves. Special end plates are attached to the end members of the stack (left and right side, grey). The end plates have electrical connectors for the external circuit as well as hook-ups for gas supply and possibly coolant. Depending on the stack's total output power and the heat generation associated with it stacks are either air- or water-cooled.

Simply by varying the number of individual cells, stacks can be designed for any desirable output voltage. Since the cells are electrically connected in series adding a cell will increase the output voltage. The total output voltage U_{Stack} is given by the sum of all of the individual voltages $U_{individual\_cell}$.



Technology

Direct Methanol Fuel Cell

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Direct Methanol Fuel Cell

The Direct Methanol Fuel Cell is a special case of the PEM fuel cell. DMFCs and PEMFCs have similar structures, two electrodes are separated by an electrolyte consisting of a proton-conducting polymer membrane that is impermeable to electrons.

The difference between a DMFC and a PEMFC is that the DMFC uses methanol (CH_3OH) as fuel, not hydrogen. At ambient pressures (1013 hPa) methanol is liquid at temperatures between - 97° C and 64° C. Thus the major advantage of a DMFC is that its fuel can be handled, stored and transported similarly to conventional liquid fuels like gasoline or diesel. On the other hand, methanol is poisonous and corrosive and DMFCs have low electrical efficiencies compared to most other fuel cell types. Applications: electric motors, portable electricity supply, battery substitute

How a DMFC works

Transparency 9 shows a schematic diagram of a DMFC. The electrolyte (PEM) is shown in yellow, the electrodes on either side of it in blue (anode on the left, cathode on the right). The anode is supplied with a methanol/water mixture (red/blue/black and red/blue molecules on the left). Due to the electrode's catalytic effect hydrogen is separated from the mixture and reduced to protons (H^+-ions, yellow +), yielding free electrons (yellow -) to the anode. Both protons and electrons now travel to the cathode side but - very importantly - on different paths. While the H^+-ions pass through the cell's proton-conducting membrane the electrons move through the (closed) external circuit and thereby provide the fuel cell's electric power (indicated by light bulb).

At the anode the oxygen and carbon left over from the methanol react with the oxygen from the water and form carbon dioxide (CO_2).

At the cathode the protons that passed through the membrane and electrons from the external circuit react with the supplied oxygen (blue) to form water (red and blue).

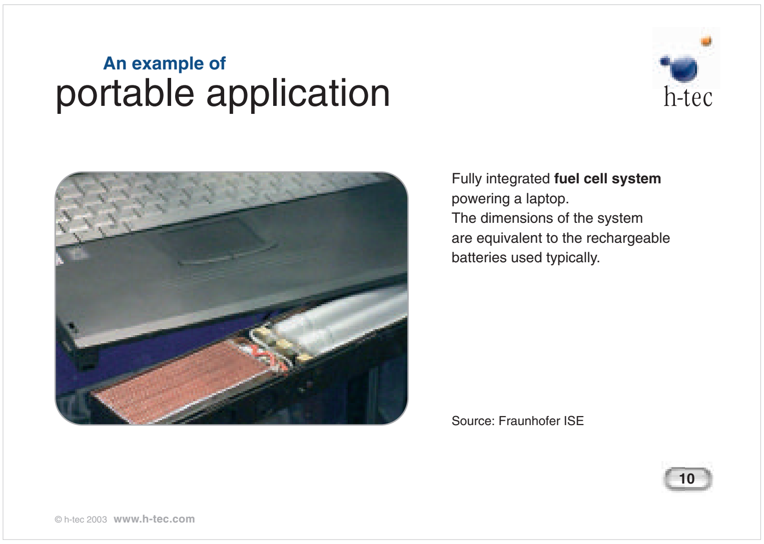
Cathode reaction:

$3O_2 + 12H^+ + 12e^- \rightarrow 6H_2O$

Anode reaction:

$2CH_3OH + 2H_2O \rightarrow 2CO_2 + 12H^+ + 12e^-$

Explanation 10



An example of
portable application

Fully integrated **fuel cell system** powering a laptop.
The dimensions of the system are equivalent to the rechargeable batteries used typically.

Source: Fraunhofer ISE

Portable Application

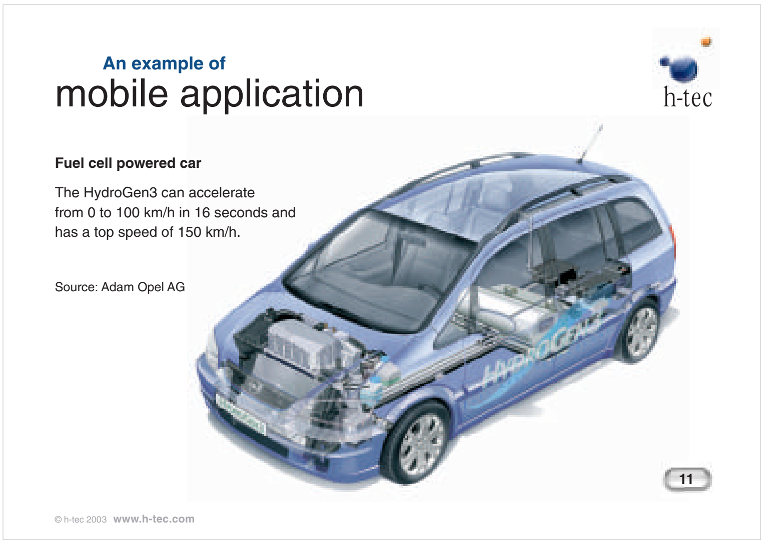
Fuel cells for portable applications

For portable applications fuel cells are an alternative to typical batteries. Their major advantage is that, unlike batteries, they do not discharge. Batteries are energy storage devices, the electrical energy they can supply is determined by the amount of chemical reactant stored within. When its reactant is used up a battery has to be either recharged (if it is rechargeable) or discarded. Fuel cells, on the other hand, are energy conversion devices and do not store their own fuel. They will provide electrical energy for as long as they are supplied with fuel (hydrogen or methanol).

There is a wide range of possible applications of fuel cell technology for portable devices, for example, fuel cells could provide electricity to low-power devices such as laptops or measuring instruments, or they might even supply power to camping equipment.

Low-temperature fuel cells like PEMFCs and DMFCs are the most suited for portable low-power devices because they are operable at low temperatures, work immediately after start-up (i.e. no warm-up phase is required) and allow for a compact design.

The only byproduct of a PEMFC is water while a DMFC - in addition to water - also produces small amounts of carbon dioxide



An example of

mobile application

Fuel cell powered car

The HydroGen3 can accelerate from 0 to 100 km/h in 16 seconds and has a top speed of 150 km/h.

Source: Adam Opel AG

Mobile Application

Fuel cells for mobile applications

Mobile applications are dominated by PEM fuel cells. Since they have low operating temperatures PEMFCs can deliver power immediately after start-up. This is particularly important for use in automobiles.

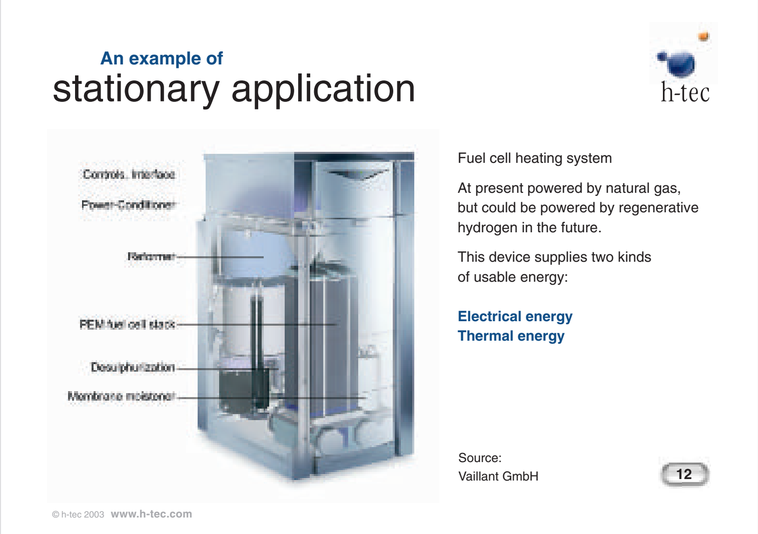
Power needs for mobile applications range from a few kilowatts to several megawatts. Small boats typically require onboard power supplies of a few kilowatts while electric power on the order of megawatts is needed to equip a submarine with adequate propulsion as well as onboard electricity and emergency energy supply systems.
Due to their modular character fuel cell stacks can be adapted to meet the most different power requirements imaginable.

The HydroGen3 made bei Opel is powered by a fuel cell stack consisting of 200 individual fuel cells that are connected in series. As there are no moving parts in a fuel cell the energy conversion is done noiselessly and without wear and tear.

BMW and DaimlerChrysler, in their research prototypes, use different technologies:

The BMW 745h uses a hydrogen combustion engine instead of a fuel cell stack and an electric motor. This technology is based on the conventional four-stroke internal combustion engine, the difference being that the engine burns hydrogen instead of gasoline. The engine has a capacity of up to 135 kW.

The NECAR5 (NECAR - New Electric Car), DaimlerChrysler's fuel cell car, runs on methanol that is reformed onboard. In a reformer hydrocarbons like methanol are transformed into hydrogen, CO_2 and CO. In this way the hydrogen for the fuel cell is produced directly in the automobile.



An example of
stationary application

Fuel cell heating system

At present powered by natural gas, but could be powered by regenerative hydrogen in the future.

This device supplies two kinds of usable energy:

Electrical energy
Thermal energy

Source:
Vaillant GmbH

Stationary application

Fuel cells for stationary applications

Stationary applications range from in-home power and heat generation (output starting at 2 KW) to heat and power supply for entire residential areas by means of heat-and-power block units (with outputs in the MW range).

Conventional block-type thermal power stations, which generate electrical power and heat through coupling rely on combustion engines and gas turbines. In comparison, fuel cells have much higher efficiencies as well as lower emissions and sound pollution.

A complete fuel cell system for generating power and heat consists not only of the fuel cell stack, but also of a number of other components:

Systems for conditioning the gas: if the fuel needed to run the fuel cell is of inadequate quality, it has to be conditioned first. This may involve reforming and CO purification as well as desulfurization and the removal of excess oxygen

Heat exchangers: serve to couple out the heat generated by the cell reaction for external use

Other power-generating components: depending on output, these may be expansion turbines, gas turbines or combined gas- and steam turbines

Piping, pumps and condensers required for gas and heat management

Electrical connections between system units as well as controls and interfaces

Invertors and transformers to convert and transform the DC voltage of the fuel cell stack to AC voltage.