RENEWABLES

Advanced Hydrogen Fuel Cell Technology

CP1064

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Introduction

The human-induced climate change and the shortage of raw fossil resources determine society, industry and politics more and more. To limit the catastrophic impact of the rapidly increasing global temperature and all following consequences on earth and to ensure future generations can still live on the planet. Therefor, more than 50 countries, as well as the entire European Union, have pledged to meet the net zero emissions scenario till 2050. [1]
The technology for the production, storage, and usage of hydrogen is a key element to reshape the fossil fuel based sectors into environmentally sustainable industries.
Hydrogen is the most abundant chemical substance in the universe. Most of the hydrogen on earth exists in molecular forms such as water and hydrocarbons.
Hydrogen for economic utilisation is categorised by the process of production: [2]

- Green hydrogen: Produced by the electrolysis of water, the electricity required for this comes entirely from renewable energies
- Yellow hydrogen: Produced by the electrolysis of water, the electricity required for this comes from the electricity mix currently available
- Violet Hydrogen: Produced by the electrolysis of water, the electricity required for this comes entirely from nuclear power
- Blue Hydrogen: Produced by steam reforming natural gas (methane) with subsequent absorption and storage of the released carbon dioxide (CO_2), low CO_2 emission
- Turquoise Hydrogen: Produced by methane pyrolysis, solid carbon as a by-product, low CO2 emission
- Grey hydrogen: Produced by steam reforming of fossil fuels, most economically lucrative so far, BUT high greenhouse gas emissions

(Renewable/ clean hydrogen: synonym for green hydrogen)

Physical and technical properties of hydrogen. [3]

Table 1: Characteristics of hydrogen

Name, symbol, atomic number	Hydrogen, H, 1
Phase at STP, element category	gas, non-metal, colourless
Density, boiling point, melting point	0,09 kg/m^3 (273 K), 21,2 K, 14 K
Isotopes	Deuterium, Tritium
Oxidation states	-1, 0, +1
Electronegativity (Pauling scale)	2,2
Heating value	141,8 MJ/kg, 12,7 MJ/m^3
Lower calorific value (ambient conditions)	≈85 % à 3 kWh/m^3 = 11 MJ/m^3
Electron configuration	1s^1

The first reference of hydrogen by the British scientist Henry Cavendish dates back to 1766. He poured different metals with acid and named the occurring gas “inflammable air”. The following chart lists various milestones on the way to our current understanding of the element hydrogen and the global hydrogen economy. [4,5]

Table 2: History of Hydrogen

1766	Henry Cavendish, production of hydrogen by the reaction of tin, zinc, iron with sulphuric acid. He describes his discovery as " inflammable air ".
1774	Carl Wilhelm Scheele and Joseph Priestley find a gas that is part of the air and call it "fire air"
1787	Antoine Lavoisier names the „fire air“ as oxygen and the „inflammable air“: hydrogen
As of 1800	Usage of hydrogen as a light gas/town gas until 1950/60, later replaced by cheaper natural gas
1808	In London, the first street lamps burn with illuminating gas/town gas (50% H_2, 30% CH_4, 10% CO, etc.)
1820	Döbereiner's lamp - a platinum catalyst is used, here to ignite an oxygen-hydrogen mixture
1842	William Robert Grove uses his „Gas voltaic battery” for the first time to demonstrate the basics of a fuel cell
1918	Haber-Bosch process, large-scale ammonia synthesis. Production of fertilizers and explosives without saltpetre now possible
1930s	The steam methane reforming process is invented
1937	Pabst von Ohain tests a jet engine with hydrogen as fuel
1960s	Hydrogen is used as fuel for the US space program
20th century	Natural gas, crude oil, and nuclear energy are cheap and always available until the oil crisis of 1973 - from then interest in hydrogen is rising again
1970s - 80s	The energy crisis and the nuclear catastrophe of Chernobyl renewed the movement towards the hydrogen economy
from 2002	Prices for crude oil/ natural gas are rising
2020	Hydrogen strategy of the European Commission

Today hydrogen is commonly known as a clean energy source. However, the utilisation of an energy carrier can only be effective, as far as the production process is environmentally sustainable. [6]
Today (2019) about 90 Mt of hydrogen is produced worldwirde, with a fraction of 60% out of natural gas. Only 2% of the hydrogen is produced via the “clean” electrolysis process. [7]
The principle of electrolysis is very simple - the splitting of water molecules by using electrical energy. It is a more expensive process compared to the established petrochemical methods due to greater energy consumption. On an industrial level, hydrogen is currently mainly obtained through facilitating fossil raw materials using the process of steam reforming and partial oxidation. [6] In addition, hydrogen is a by-product in other technical/chemical processes such as isomerization/aromatization or chlor-alkali electrolysis.

Steam reforming

Steam reforming generally refers to the reaction of hydrocarbons with water, where the products are carbon monoxide and hydrogen. Steam methane reforming (SMR) is the most common method of hydrogen production. The methane comes mainly from natural gas. Due to the (yet) cheap natural gas and the well-optimized reactor structure, SMR is currently the cheapest method for producing hydrogen: [8]

Reaction equation: $CH_{4\,(g)} + H_2O \leftrightarrow CO_{(g)} + 3H_{2(g)}$

This reaction is strongly endothermic. The conversion of the natural gas, therefore, happens in gas-heated tube furnaces with a nickel-based catalyst bed. The reactors are made of stainless steel to withstand high temperatures (up to 1000°C) and high pressures (20-40 bar) during the process.
As an alternative to methane, hydrocarbons with a chain length of C5-C8 can also be used. However, the usage of long-chain hydrocarbons automatically introduces more impurities from the reactants into the process. These impurities, specifically sulphur, can lead to the poisoning of the nickel catalyst. To encounter this, the process parameters have to be adjusted and a platinum catalyst is used to run the process economically. The steam reforming can also be combined with the partial oxidation described below to enable autothermal process control. [9,10]

The advantage of this process is that no complex heated reactors are required due to the incineration. The disadvantage is the lower H_2-CO ratio compared to steam reforming i.e., much larger reactors are required to produce the same amount of hydrogen. There are two different ways for the partial oxidation of hydrocarbons:

Noncatalytic Partial Oxidation	Catalytic Partial Oxidation
Partial Oxidation without a catalyst is performed at very high temperatures to ensure all starting materials can be converted. In addition, further cleaning steps of the reactor and the products are necessary after the oxidation to bind and remove the soot. Gasification, especially of heavy oil fractions, has become more important in recent years since the demand for heavy oil is decreasing and these products of oil production still have to be processed.	The Partial Oxidation with a catalyst takes place up to approx. 800-900°C. Rhodium is usually used as the catalyst. The selection of suitable catalysts is particularly important in this process since the catalyst needs to be protected from poisoning by sulphur or oxidization by oxygen. [9,10]

Gasification

A special operation of partial oxidation is coal gasification. This process was already executed 200 years ago to produce the so-called "town gas", which was the main source of light and heat for the population in all major cities in Europe until it was replaced by cheaper natural gas in the 1950s. During the process, the coal is heated to approx. 900°C and becomes gaseous. Partial oxidation takes place together with water vapor in the presence of atmospheric oxygen: [6]

$$C + H_2O \rightarrow CO + H_2$$

Other important definitions related to the technical production of hydrogen from fossil fuels are:
Syngas
A mixture of hydrogen and carbon monoxide; produced via natural gas, crude oil, or coal
Subsequent processing is very complex; syngas is used e.g.: ammonia synthesis, Fischer-Tropsch process, methanation, methanol synthesis

Water-gas shift reaction
also known as carbon monoxide conversion
Removing carbon monoxide with water

Gas purification
After the carbon monoxide conversion, the gas cleaning step can be carried out to ensure further purification of the products
The product is hydrogen with a purity of 96%, the methane that is still formed does not interfere with most other possible uses

Chlor-alkali process

Chlorine is one of the most important raw materials in the chemical industry. A major reason for this is its reactivity. It is used directly for water chlorination, pulp bleaching, or polymerisation to form polyvinyl chloride (PVC). In addition, chlorine plays a role in the production of epichlorohydrin (pesticides, epoxy resins), solvents, chloromethane (silicone adhesives, paints, cosmetics), Polytetratrafluorethylene isocyanates (upholstery material, insulation). The total production of chlorine in 2021 was about 90 Mt. [11, 12]
Chlorine is mainly produced from sodium chloride (NaCl), but also from other salts or by hydrochloric acid electrolysis. The main processes of chlor-alkali electrolysis are:

Membrane cell process
Diaphragm cell process
Mercury cell process

Table 3: Production of chlorine [11]

Process	Advantage	Disadvantage
Diaphragm cell	low standards for the brine low specific energy consumption	usage of asbestos diaphragm high heat demand for the NaOH concentration low NaOH purity sensitive for pressure variations within the cell
Mercury cell	50% NaOH directly from the cell high purity of Cl_2 and H_2 easy cleaning of the brine	usage of mercury requires high purity brine high costs for running the cell high costs for environmental engineering large space requirement
Membrane cell	low specific energy consumption low investment costs low operation costs high purity NaOH solution insensitive to alternation of load or shut-offs further potential for improvement	highest requirements for the purity of the brine high concentration of O_2 in the Cl_2 high cost of the Membrane

Theory

Basics of electrochemistry

Electrochemistry is a part of physical chemistry and has been studied since the 18th century. Historical examples are the experiments of Alessandro Volta (voltaic pile, 1799) and Michael Faraday (electrolysis, 1832) which are the foundation of a new perspective for the course of chemical reactions. Today, electrochemical processes are fundamentally integrated into technical chemistry and process engineering. The processing and production of all goods relevant to the global economy would not be possible without them. Examples are the production and operation of all types of batteries or the production of aluminium from bauxite (fused-salt electrolysis). To understand the role of electrolysis in the decomposition of water, it is necessary to know and understand the basics of electrochemistry.

Every electrochemical reaction involves the transfer of electrons to a reactant. This transfer does not take place directly, as in a normal chemical reaction, but via an electronic conductor. This is the main difference between a chemical and an electrochemical reaction. **A chemical reaction** can always be determined based on the individual reactions of the reactants. If this reaction runs via the donation of electrons, this reaction step is referred to as oxidation. The acceptance of electrons is called reduction. The overall reaction is a combination of electron donation and electron acceptance (oxidation and reduction), it is called a redox reaction.

Example: Exothermic welding (historical process for joining rails)

Overall reaction: $Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3$

Reduction: $2Fe^{3+} + 6e^- \rightarrow 2Fe$

Oxidation: 2 $Al \rightarrow 2Al^{3+} + 6e^-$

Historical exothermic welding is a chemical reaction, the reduction and oxidation do not occure spatially separately.

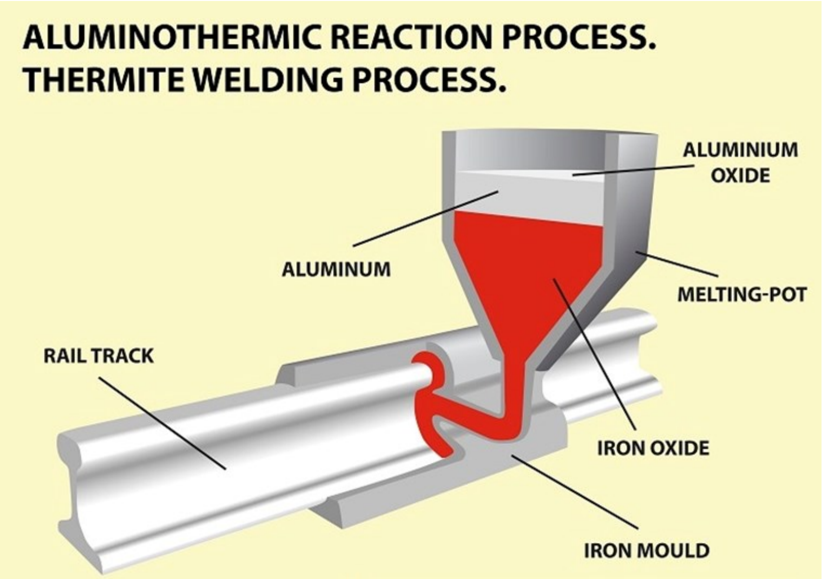


Figure 1: Exothermic welding

All compounds involved in a chemical/electrochemical reaction have a different affinity for accepting or donating electrons, which is based on atomic structure. Thus, one reaction partner always strives to take up electrons and one to give them away. The result is a flow of electrons from the electron-donating reaction partner (reducing agent) to the electron-accepting reaction partner (oxidizing agent). The difference between the different affinities is called “potential” - or to be more specific: redox potential.

If reduction and oxidation take place at separate locations, this is referred to as **an electrochemical reaction**. Both reaction spaces are connected by an electron-conducting material, which allows electrons to flow and thus electrical work to be performed.

An example of such an electrochemical reaction is the Daniell element, which was introduced by John F. Daniell in 1836:

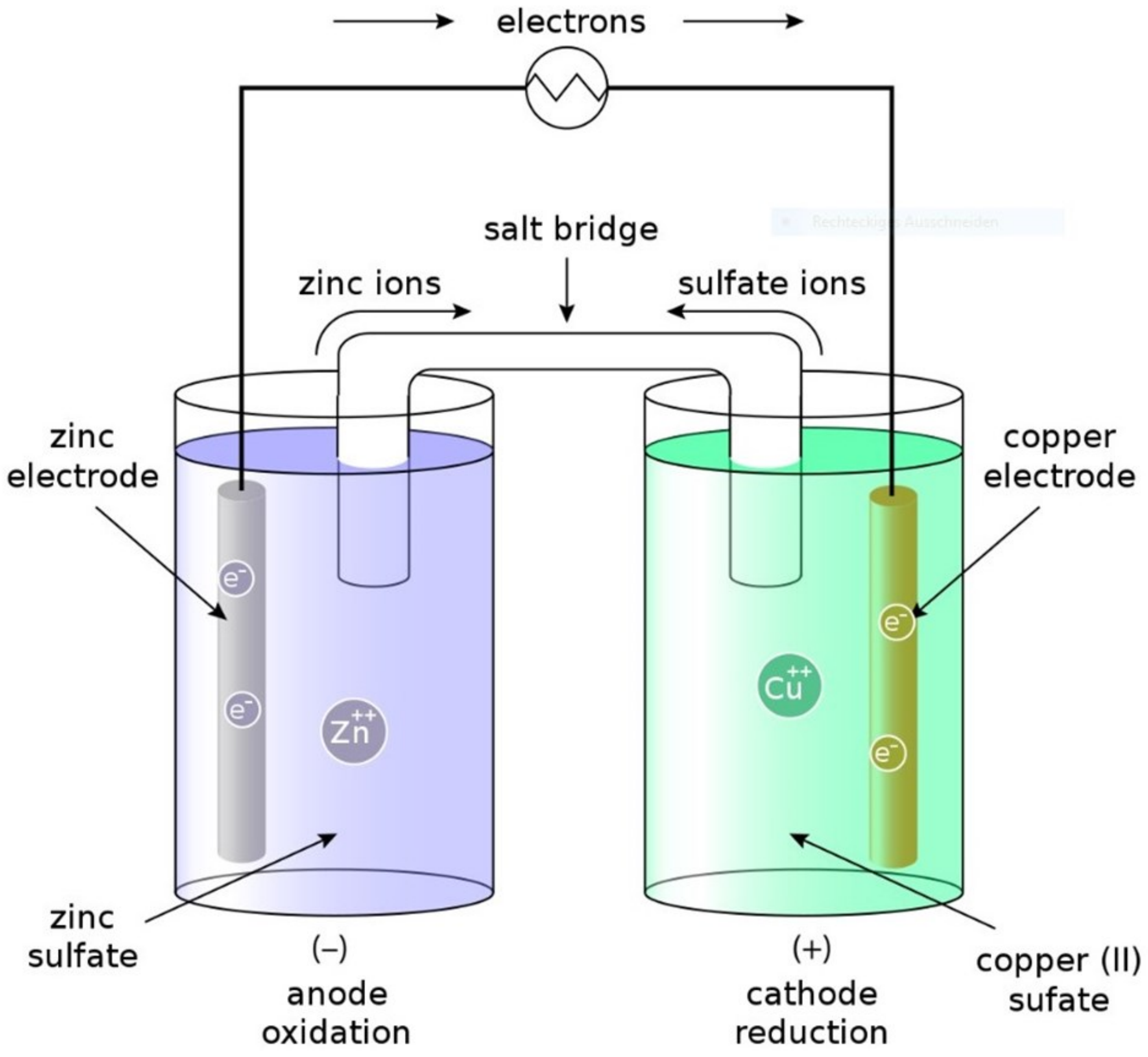


Figure 2: Daniell Element

Overall reaction $Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$

Reduction: $Zn \rightarrow Zn^{2+} + 2e^-$

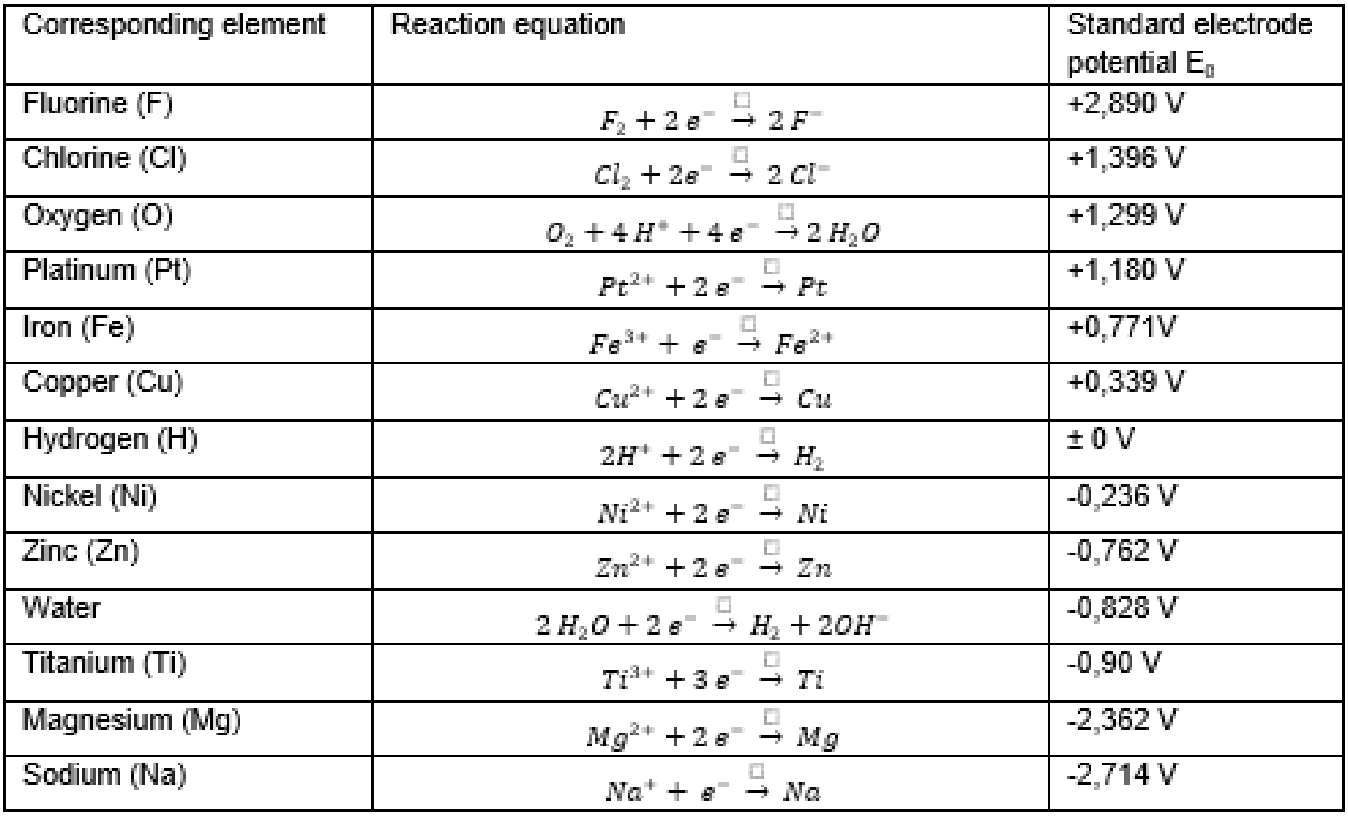
Oxidation: $Cu^{2+} + 2e^- \rightarrow Cu$

On the one side, a zinc electrode is immersed into a zinc sulphate solution, on the other side, a copper electrode is immersed into copper sulphate. Both solutions are spatially separated from each and cannot mix. They are connected by a salt bridge (e.g. KCl), so ions can pass from one solution to the other. The two electrodes are also conductively connected. The electrons now flow from the zinc electrode to the copper electrode. This flow of electrons can be measured and used. The zinc electrode dissolves over time as more and more zinc ions lose their electrons and then merge into the solution. At the copper electrode, the copper ions in the copper sulphate solution accept the electrons and are reduced to elemental copper, which is deposited on the electrode. Under normal conditions, this process takes place voluntarily, i.e. without the influence of an external force.

An electrochemical reaction always needs an electron-donating and an electron-accepting reactant. The reaction itself can either take place voluntarily, with the release of electrical energy (as mentioned in the example) - or not voluntarily, through the supply of electrical energy (e.g. chapter chlorine-alkaline electrolysis). In both cases, the electrode where reduction occurs is called the cathode and the electrode where oxidation occurs is called the anode.
Whether an electrochemical reaction (under normal conditions) takes place voluntarily or not can be predicted with the help of the standard electrode potential E_0.

The standard electrode potential is an experimentally determined cell voltage (potential difference) between a standard hydrogen electrode (which is assigned the value ±0 V) and the respective reference electrode under standard conditions. A selection of some standard potentials can be found in Table 4.

Table 4: Galvanic series (selection)
The order of the redox reactions according to their standard electrode potentials is referred to as the galvanic series. With the Nernst equation it is possible to calculate the redox potential under other reaction conditions:



Corresponding element	Reaction equation	Standard electrode potential E_0
Fluorine (F)	$F_2 + 2\,e^- \overset{\square}{\rightarrow} 2\,F^-$	+2,890 V
Chlorine (Cl)	$Cl_2 + 2e^- \overset{\square}{\rightarrow} 2\,Cl^-$	+1,396 V
Oxygen (O)	$O_2 + 4\,H^+ + 4\,e^- \overset{\square}{\rightarrow} 2\,H_2O$	+1,299 V
Platinum (Pt)	$Pt^{2+} + 2\,e^- \overset{\square}{\rightarrow} Pt$	+1,180 V
Iron (Fe)	$Fe^{3+} + e^- \overset{\square}{\rightarrow} Fe^{2+}$	+0,771V
Copper (Cu)	$Cu^{2+} + 2\,e^- \overset{\square}{\rightarrow} Cu$	+0,339 V
Hydrogen (H)	$2H^+ + 2\,e^- \overset{\square}{\rightarrow} H_2$	± 0 V
Nickel (Ni)	$Ni^{2+} + 2\,e^- \overset{\square}{\rightarrow} Ni$	-0,236 V
Zinc (Zn)	$Zn^{2+} + 2\,e^- \overset{\square}{\rightarrow} Zn$	-0,762 V
Water	$2\,H_2O + 2\,e^- \overset{\square}{\rightarrow} H_2 + 2OH^-$	-0,828 V
Titanium (Ti)	$Ti^{3+} + 3\,e^- \overset{\square}{\rightarrow} Ti$	-0,90 V
Magnesium (Mg)	$Mg^{2+} + 2\,e^- \overset{\square}{\rightarrow} Mg$	-2,362 V
Sodium (Na)	$Na^+ + e^- \overset{\square}{\rightarrow} Na$	-2,714 V

$$E = E_0 + \frac{R * T}{z * F} * \ln \frac{c_{Ox}}{c_{Red}}$$

E	Redox potential
E_0	Standard potential
R	Gas constant
T	Temperatur in K
F	Faraday constant
Z	Number of electrones exchanged
$c_{Ox/Red}$	concentration oxidant/ reducing

The redox reaction with the more negative standard potential is always the electron-donating process in chemical reactions. With the help of the standard potential, a method has been established to use electrochemical reactions in a targeted manner to generate electrical energy. The standard electrode potential establishes the basic framework for the construction of:
Primary cell: non-reversible redox reaction à battery (e.g. Alkaline battery)
Secondary cell: reversible redox reaction à accumulator, i.e. by forcing electric energy into the system the initial condition of the cell can be recovered
Fuel cell: produces (electric) energy through the continuous feed of oxidant and reductant.

A chemical process in which a redox reaction is initiated by force (via electric current) is called electrolysis. An example of electrolysis would be applying a voltage to the Daniell element. This allows the oxidation and reduction processes to be interchanged.
(See figure 2)

Overall reaction: $Zn^{2+} + Cu \rightarrow Zn + Cu^{2+}$

Reduction: $Zn^{2+} + 2e^{-} \rightarrow Zn$

Oxidation: $Cu \rightarrow Cu^{2+} + 2e^{-}$

The negative pole of the voltage source needs to be more negative than the potential of the zinc electrode, so the electrons can flow to the zinc. The total voltage applied must therefore be at least as large as the potential of the Daniell element. In practice, the applied voltage is higher. An overvoltage is required to compensate for kinetic inhibitions, electrode resistances, or side reactions. In electrolysis, reduction takes place at the cathode and oxidation at the anode. It should be noted, however, that in contrast to the voluntary reaction, the poles are reversed.

Water electrolysis

In 1800, chemist William Nicholson and physician Anthony Carlisle used a voltaic pile to split water, resulting in two gases in a 2:1 ratio. This first experiment (more than 200 years ago) started the production of hydrogen from water. As a result, the technical splitting of water was continuously developed.
With the Gramme machine, the complex battery construction could be eliminated and in 1888 Dmitri A. Lachinov proposed the production of hydrogen and oxygen from water by electrolysis and submitted several patents intending to use oxygen in the steel industry. However, the enormous demand for electrical energy made it difficult to meet the increasing demand for hydrogen over time. Large electrolysis plants were completed in 1929 next to a hydroelectric power station in Rjukan (Norway) or next to the Aswan High Dam in 1960. With the large-scale implementation of the Haber-Bosch process, hydrogen was finally established as a basic material in the chemical industry. Then as now, however, the same problem was encountered again and again - enormous amounts of energy are required for the electrolysis of water. [9,13]
For the past 100 years, the problem was “solved” by developing more and more techniques to produce hydrogen from fossil fuels (see chapter 3). This was as successful as it was wrong, as we have to realise today. In times of climate change, the focus is again on the electrolysis of water. The further development of energy production from the sun and wind allows us to meet the global economy’s demand for hydrogen.

The modern processes for water electrolysis can be classified according to the type of electrolyte used:

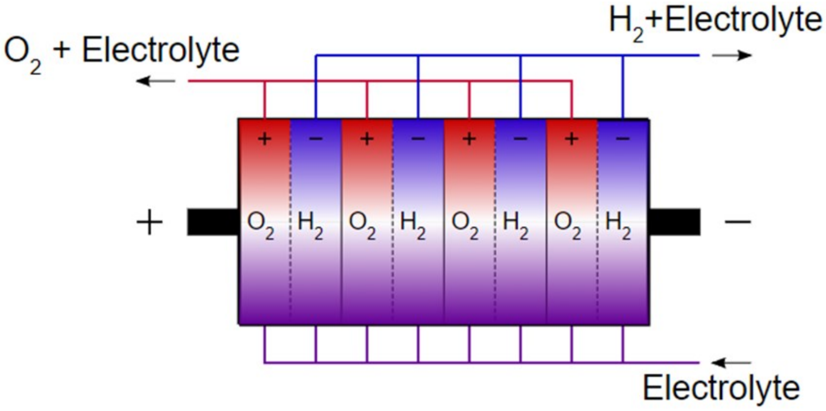
1. Alkaline electrolysis
2. High-temperature electrolysis
3. Membrane electrolysis

Other hydrogen production processes that are currently still in development are: [16]

- Biomass gasification and pyrolysis
- Biological production
- Photolytic splitting of water
- Nuclear-related pathways
- Photo-electrochemical methods
- High-temperature thermochemical methods
- Fuel cell-based co-production

Alkaline Electrolysis

Alkaline electrolysis is the most common and best-developed electrolytic process to produce hydrogen. A 20% - 40% potassium hydroxide solution (KOH) is usually used as the electrolyte, in which electrodes made of a nickel alloy are immersed. The process temperature under normal pressure is about 60°C - 90°C. The electrodes are constantly flushed with the electrolyte solution. The resulting gas must be constantly discharged. The distance between the electrodes should be as small as possible to reduce the cell resistance, but this also makes it more difficult to discharge the gases that are produced. [14]
Figure 3 provides an example of the structure of an alkaline electrolyser.



Overall reaction: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$

Reduction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Oxidation: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$

Solid oxide electrolysis

The principle of a solid oxide electrolyser cell was developed in the 1980s. It should be noted that the term High-Temperature Steam Electrolysis (HTSE) characterises the entire process of hydrogen production and the Solid Oxide Electrolysis Cell (SOEC) is only a part of it. Solid oxide electrolytic cells generally operate at 450°C - 1000°C. Such a cell consists of three main components: a fuel electrode, into which the fuel (i.e., water) is fed, a solid electrolyte, and an oxygen electrode. A distinction is made between the two main designs for such electrolytic cells, depending on the type of electrolyte. There are proton-conducting electrolytes (P-SOEC) and oxygen ion-conducting electrolytes (O-SOEC). [14]

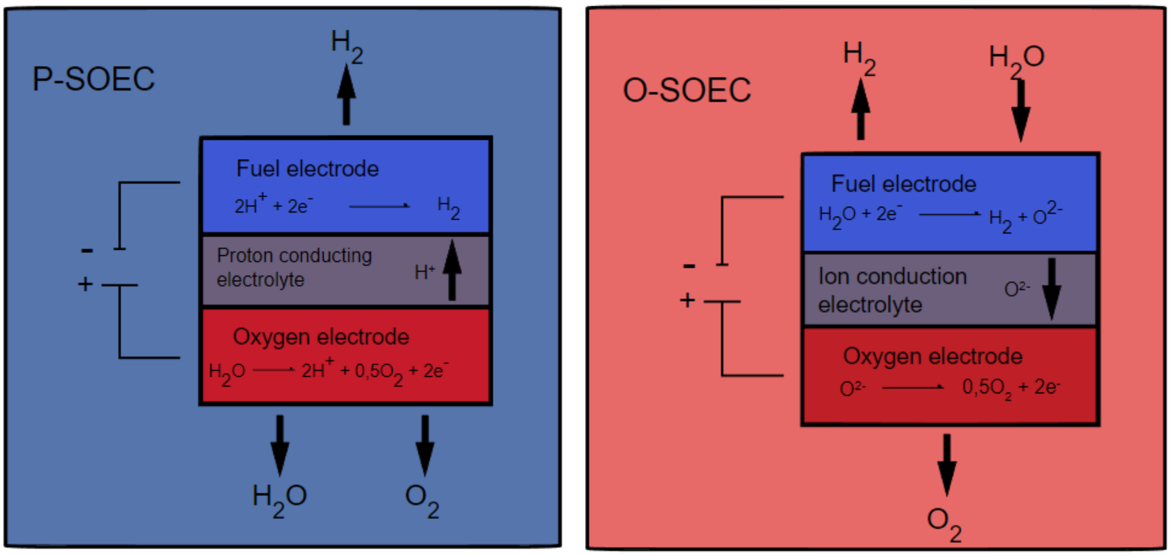


Figure 4: Schematic representation of solid oxide electrolysis cell working principle

Membrane process

Historically, the use of polymers for electrolysiswent back to the US space program and the developments of the DuPont company in the 1960s. DuPont developed a membrane based on polytetrafluoroethylene (PTFE). The polymer, which is still known today under the brand name Nafion®, is selectively conductive for protons or other cations. Anions, on the other hand, cannot pass through the membrane. In addition to PTFE, polymer membranes were often also manufactured based on polyetheretherketone (PEEK). These have the advantage that they can be produced without the environmentally complicated fluorine. However, they do not have the chemical resistance of PTFE. All polymer membranes usually have a thickness of 50-250 µm and, due to their proton-conducting properties, serve as a solid electrolyte in the electrolysis of water. An efficiency of up to 80% at 1 A cm^{-2} can be achieved. Distilled water (or fresh water) is used for electrolysis as the use of saltwater leads to corrosion of important system elements. In contrast to alkaline electrolysis, it is possible to operate the PEM electrolyser in reverse mode as a fuel cell for electricity production. [14]

Table 5: Advantages and disadvantages of the membrane process

Pros	**Cons**
No corrosive electrolyte	Expensive manufacturing of the membrane
Possible under high current	Acidic polymer are negative for durability
Possible under high pressure	Complex cell construction = high investment cost
High purity of products	
Performs well on inconsistent power sources	
Versatile and compact, can also be used in small systems	

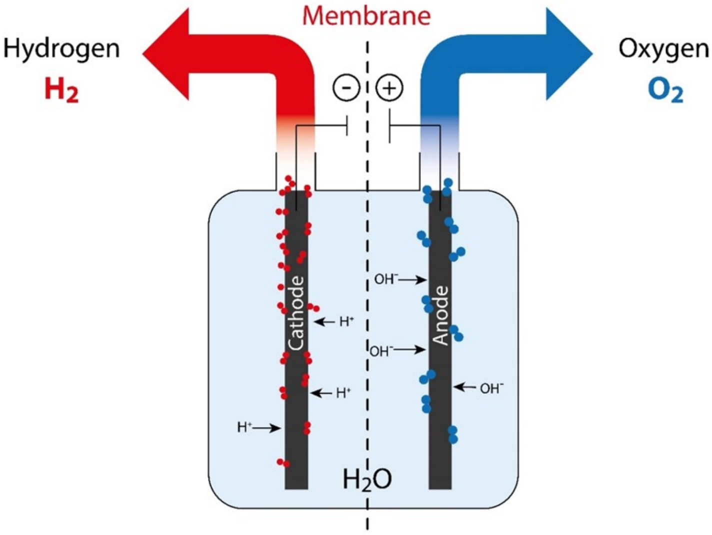


Figure 5: Schematic representation of the membrane electrolysis process

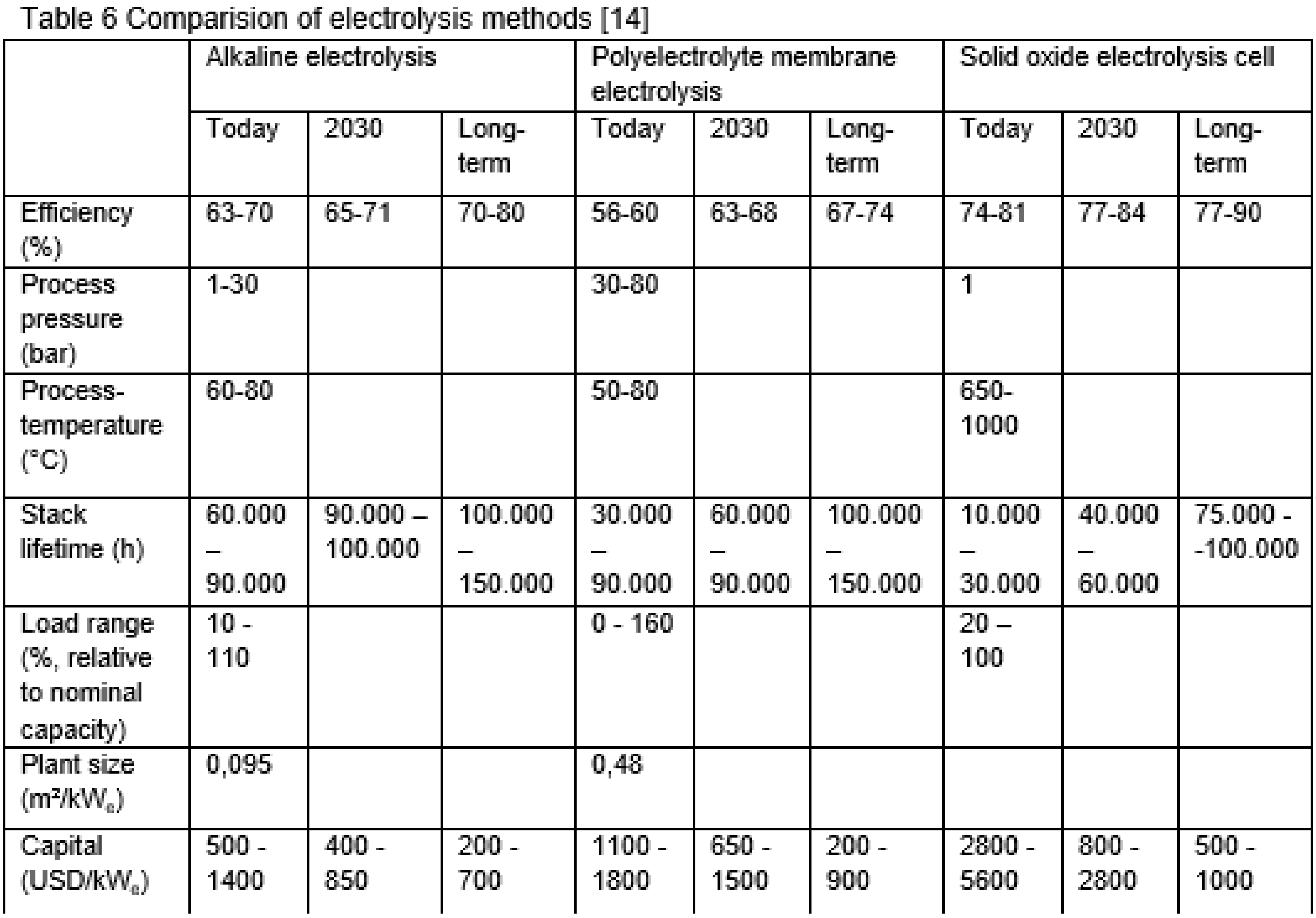


Table 6 Comparision of electrolysis methods [14]

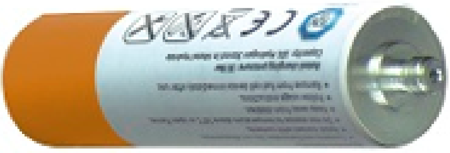
	Alkaline electrolysis			Polyelectrolyte membrane electrolysis			Solid oxide electrolysis cell		
	Today	2030	Long-term	Today	2030	Long-term	Today	2030	Long-term
Efficiency (%)	63-70	65-71	70-80	56-60	63-68	67-74	74-81	77-84	77-90
Process pressure (bar)	1-30			30-80			1		
Process-temperature (°C)	60-80			50-80			650-1000		
Stack lifetime (h)	60.000 – 90.000	90.000 – 100.000	100.000 – 150.000	30.000 – 90.000	60.000 – 90.000	100.000 – 150.000	10.000 – 30.000	40.000 – 60.000	75.000 - -100.000
Load range (%, relative to nominal capacity)	10 - 110			0 - 160			20 – 100		
Plant size (m^2/kW_e)	0,095			0,48					
Capital (USD/kW_e)	500 - 1400	400 - 850	200 - 700	1100 - 1800	650 - 1500	200 - 900	2800 - 5600	800 - 2800	500 - 1000

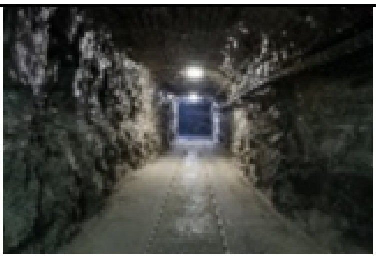
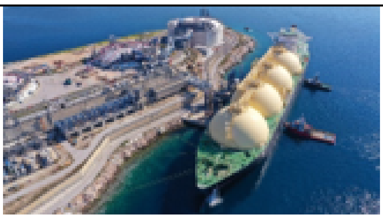
Theory

H2 Transport and Storage

Efficiency and fairness of the storage and distribution of hydrogen are important aspects on the way to realize a new branch of the economy. In the past, sustainable production or economic use has always been at the centre of political and industrial development. New ways to store or trade hydrogen in an energy-efficient manner need to be found for the enormous volumes that will be produced in the future. Established methods, which are known from the handling of natural gas or other technical gases, are suitable for this purpose.

Table 7: Storage and distribution of hydrogen [5]

Storage methods			
Chemical Storage	Metal hydride storage	Stationary and mobile	 Figure 6: Metal hydride storage
	Chemical conversion	Existing infrastructure	 Figure 7: Storage via H_2 chemical compound
Liquid Storage	Cryo-storage	Mobile	 Figure 8: H_2 truck transport
		Stationary big storage	 Figure 9: H_2 large storage

Storage methods			
Pressured storage	Gas storage	Natural gas storage/ salt cavern	 Figure 10: H_2 cavern storage
		Stationary and mobile	 Figure 11: H_2 gas storage
Distribution			
Land transport		Truck	 Figure 12: H_2 truck Transport
		Pipeline	 Figure 13: H_2 pipeline
Ocean transport		Transport ship	 Figure 14: H_2 tankship
		Pipeline	 Figure 15: H_2 submarine pipeline

There have been numerous possible applications for hydrogen in the industry and energy sector for the past 50 years. Due to the greater awareness of global climate change, these technologies are increasingly coming into focus and the possibilities of using them for electrification, energy storage, or fuel production are constantly under development. Below you get a brief overview of the various possibilities: [17]

1. Hydrogen as an energy carrier Hydrogen only exists in molecular form on earth and must first be produced by using suitable technologies. The respective process makes it an energy carrier, whether through production using renewable energies, industrial processes, or chemical reactions. The chemical energy that is "stored" in these processes by the hydrogen produced, can be recovered to a certain percentage through the particular application. Hydrogen has the advantage that its use is hardly harmful to the environment and can be used in a variety of ways. The disadvantage, however, is the high cost of storing (and producing) hydrogen.

2. As energy storage The possibility of hydrogen storage and thus the use of hydrogen as an energy storage medium are various. However, the low density determines that parts of the conventional technologies need to be improved. Large amounts of gaseous hydrogen can therefore only be stored in suitable caverns and salt domes. Otherwise, storage in pressure vessels or cryo-terms is usually used. Another storage option is chemical storage in H2 compounds. These have the advantage that the necessary infrastructure is already existing. Storage in the form of metal hydride storage, in which the hydrogen molecules are held in the metal grid of the storage, as in the H2 Storage Module (1200-18), is also possible. (see Chapter 6)

3. As a fuel A mixture of oxygen and hydrogen is highly flammable and explosive. The basic prerequisite for the use of H2 in classic combustion engines is existing. However, hydrogen has a lower energy density than petrol or diesel, which means that instead of a four-cylinder engine, you would need a larger one with 8-12 cylinders to achieve the same effect. This makes the use of H2 as a replacement for classic petrol in private vehicles rather unattractive. Nevertheless, there were and still are experimental studies to convert larger engines, such as those in trucks or ships, to hydrogen anyway. [8] In addition, hydrogen can be used via Fischer-Tropsch synthesis to produce high-chain hydrocarbons and thus produce fuel.

4. Use in stationary fuel cells The use of hydrogen in fuel cells has also gained importance for the general public as a result of the efforts to fight global climate change. Today there are attempts to install stationary fuel cells in family homes and provide electrification, as well as replace classic gas heating. [18,19] Fuel cells with a proton exchange membrane are suitable for this, just as solid oxide fuel cells or molten carbonate fuel cells.

5. Use in mobile fuel cells The use of hydrogen for fuel cells in motorised vehicles is becoming more and more attractive. Up to now, there are no alternative technologies with such great potential for mass deployment. Hydrogen, stored either as a gas under high pressure or as a liquid, can be used to drive a vehicle with an electric motor (FCEV) using a PEM fuel cell. This makes it possible to replace a significant proportion of classic combustion engines and thus CO2 sources with environmentally friendly fuel cells. There are already pilot projects in which fuel cells are used in trains or airplanes. Motorised vehicles can be distinguished by: [8]

- Hybrid electric vehicle (HEV): classic hydrocarbon-based combustion engine and in addition an electric engine.

- Battery electric vehicle (BEV): only electric engine and batterie-based electric energy storage

- Plug-in hybrid electric vehicle (PHEV): HEV with the option to charge the batteries external

- Fuel cell electric vehicle (FCEV): hydrogen-based electric engine, completely electric powertrain

6. Direct use of Hydrogen Hydrogen is traditionally used in hydrocracking and hydrotreating processes to refine fuels.
   In addition, hydrogen is a cornerstone of the Haber-Bosch process in the chemical industry and thus for the production of fertilizers and explosives. In addition, there have been attempts to use hydrogen in the steel industry for reduction. [14]

The research, improvement, and dissemination of the hydrogen fuel cell technology is currently a priority for politics and industry. However, other fuel cell technologies also exist. Fuel cells enable the storing of electrical energy from wind and solar power plants as chemical energy. In this way, they make this energy usable as efficiently as possible.

In general, they combine important properties of classic combustion engines and batteries.

In a combustion engine the respective fuel and atmospheric oxygen are continuously supplied. The mixture is ignited and an explosion drives the piston. The chemical energy of the reactants is partly converted into usable mechanical energy, with a large part being lost as thermal energy. Thereafter, the reaction products are removed from the reaction space. The mechanical energy can either be used directly or converted into electrical energy. Due to the high losses in the form of thermal energy, the internal combustion engine is a very inefficient way of converting energy compared to other types of drive. [20,21]

A battery is a closed reactor, in which all substances involved in the chemical reaction are located during the entire life circle. Here, the chemical energy is converted directly into electrical energy, with a low percentage lost as thermal energy. The reaction products remain in the battery. Depending on the chemical reaction batteries are classified as a primary battery, if the reaction is irreversible. A secondary battery refers to a rechargeable battery or accumulator. The battery can be recharged by applying a voltage, i.e. the underlying chemical reaction is reversed by supplying electrical energy. The charging times are long and depend on the type and size of the battery. [20,21]

The general fuel cell successfully combines some of the properties of the internal combustion engine and battery into a technology for the future. Figure 16 shows the schematic structure of a fuel cell. The several types of fuel cells differ mainly in the underlying chemical reaction.

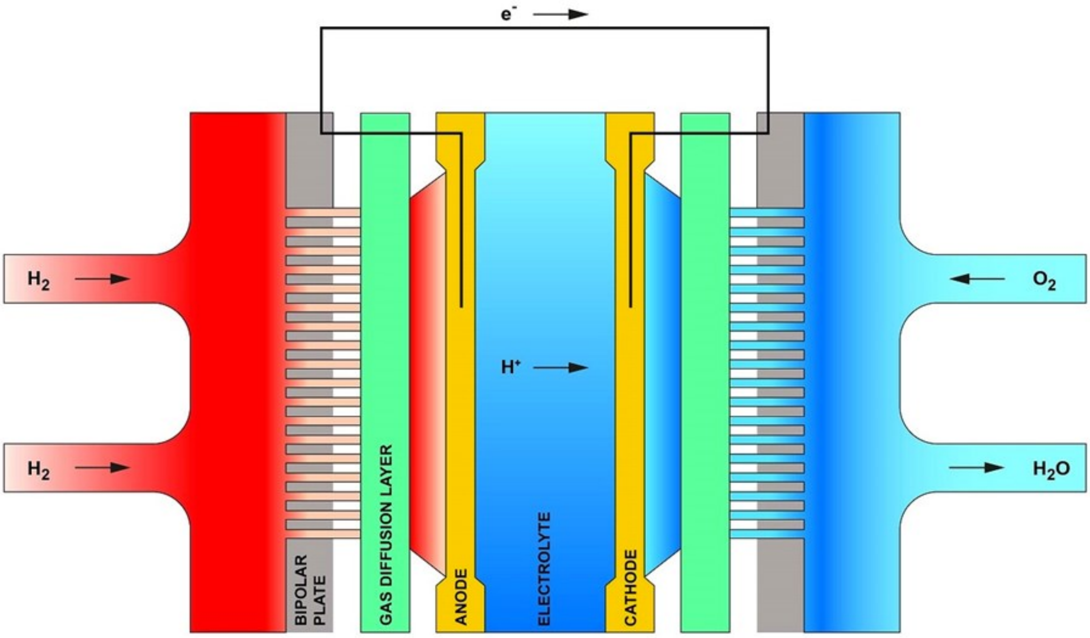
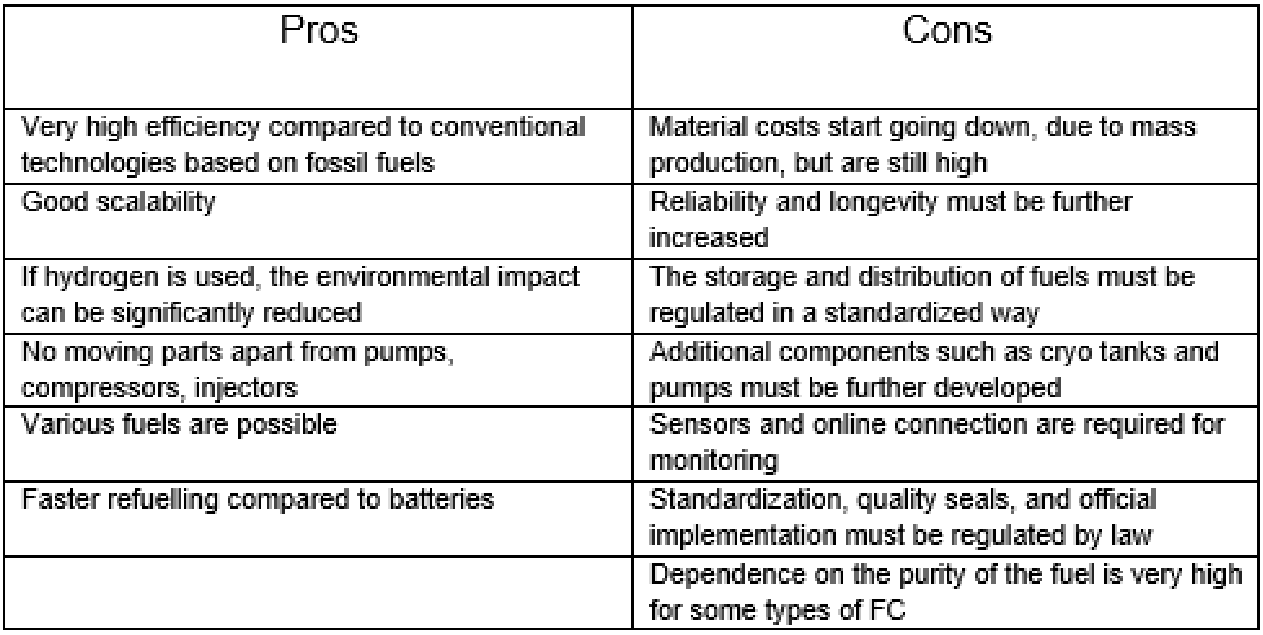


Figure 16: Generic fuel cell

As in a combustion engine, both fuel and oxidizing agents are continuously supplied from the outside. The reaction converts chemical energy into electrical energy, just like in a battery. The reaction products are then removed from the fuel cell. In the ongoing redox reaction, the oxidation and reduction steps are spatially separated from one another. This is made possible by the implementation of an electrolyte. The electrolyte allows ions to flow from the anode (negative pole) to the cathode (positive pole). The free electrons cannot take this path and need to move through an electrical conductor or consumer. This is how an electric current is induced. Both liquids (acids and bases) and solids (ceramics or membranes) serve as electrolytes.

Table 8: Advantages and disadvantages of fuel cells



Pros	Cons
Very high efficiency compared to conventional technologies based on fossil fuels	Material costs start going down, due to mass production, but are still high
Good scalability	Reliability and longevity must be further increased
If hydrogen is used, the environmental impact can be significantly reduced	The storage and distribution of fuels must be regulated in a standardized way
No moving parts apart from pumps, compressors, injectors	Additional components such as cryo tanks and pumps must be further developed
Various fuels are possible	Sensors and online connection are required for monitoring
Faster refuelling compared to batteries	Standardization, quality seals, and official implementation must be regulated by law
	Dependence on the purity of the fuel is very high for some types of FC

PEM Fuel cells

The PEM FC (**P**olymer **E**lectrolyte **M**embrane **F**uel **C**ell) is a special type of fuel cell based on a solid electrolyte material. It is the same type of membrane that was already discussed in Chapter 5 on PEM electrolysis. Due to significant technological breakthroughs, this type of fuel cell has made a great leap in development over the past 20 years. The wide range of possibilities in stationary and mobile systems are made by low operating temperature, the high power density, and the short start-up times of the PEM fuel cell. Figure 17 shows the schematic structure of a fuel cell with a polymer membrane:

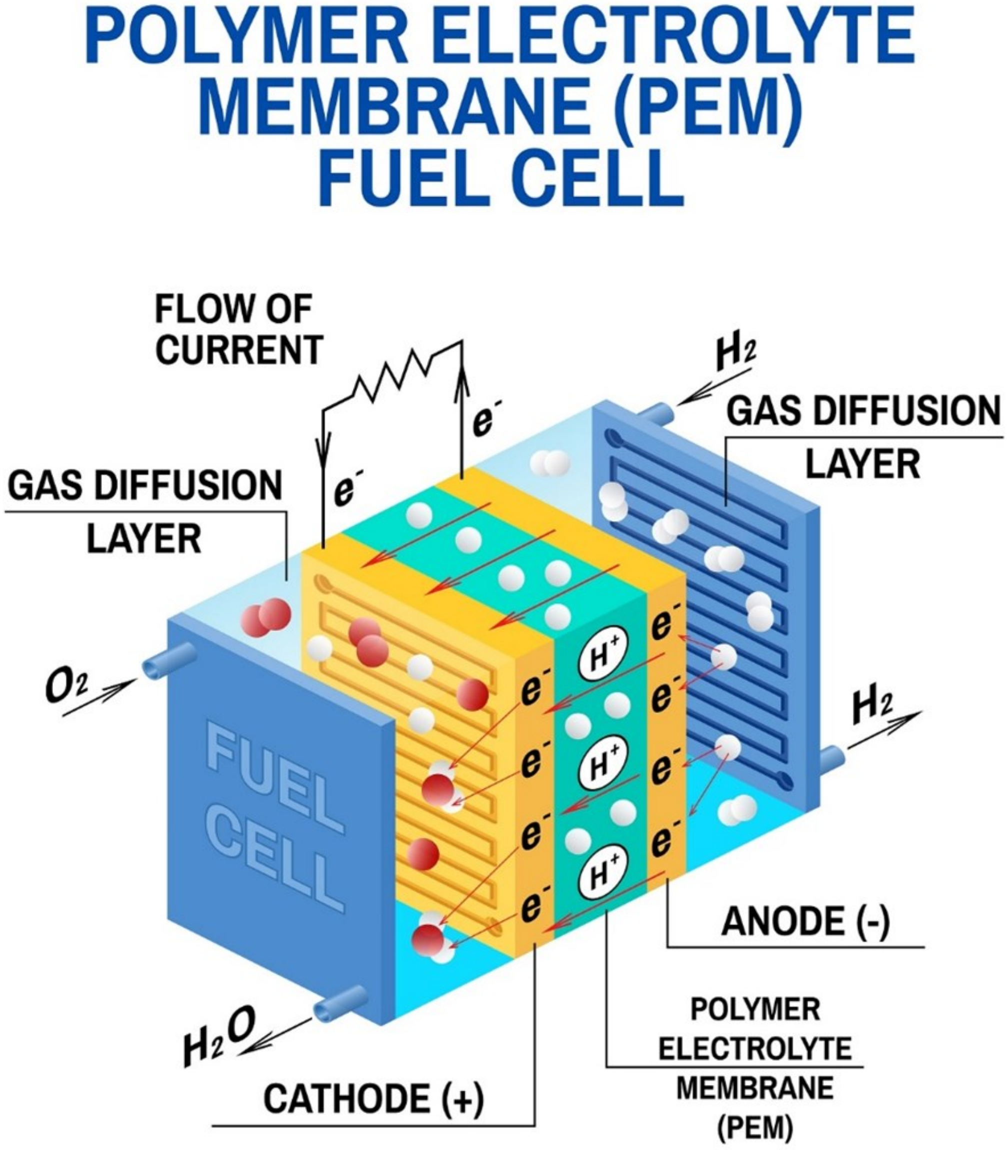


Figure 17: PEM fuel cell

In addition to the membrane, the construction of the gas diffusion layer and the electrodes is crucial for the operation of the PEM fuel cell. The membrane itself is significantly thinner than in the electrolysis process (<50 µm). It is covered with a 2-3 nm layer of (Pt) catalyst material and an extra layer of carbon to further increase the reactive surface. The gas diffusion layer (GDL) ensures that reactant gases are supplied to the active surface. In addition, it stabilizes the structure of the membrane. The water emerging during the reaction is also transported away by the GDL to free the reactive catalyst centers again. It consists of woven or non-woven carbon fibers. The gas is conducted to the GDL via 2-4 mm wide channels. The anode reaction and the cathode reaction take place separately from each other on the respective side: [16,20,22,]

Overall reaction $2\,H_2 + O_2 \rightarrow 2\,H_2O$

Reaction Anode (Oxidation, negative pole): $2\,H_2 + 4\,H_2O \rightarrow 4\,H_3O^+ + 4\,e^-$

Reaction cathode (Reduction, positive pole): $O_2 + 4\,H_3O^+ + 4\,e^- \rightarrow 6\,H_2O$

In theory, a single fuel cell can generate up to 1.23 V. In practice, the voltage is often around 0.7 V. To achieve the range of performance from 1 kW to the megawatts required in industry and the private sector, several individual cells are connected in series. This series connection and the typical design associated with it, as shown in figure 18, is referred to as a fuel cell stack. Due to the stack design, it is necessary to operate additional peripheral devices such as injection nozzles, pumps, cooling, gas (pressure) storage, and sensors for monitoring. These additional components increase the space requirements of the stack and the costs. Depending on the application (mobile or stationary) there are great opportunities for further development and optimisation with these process components.

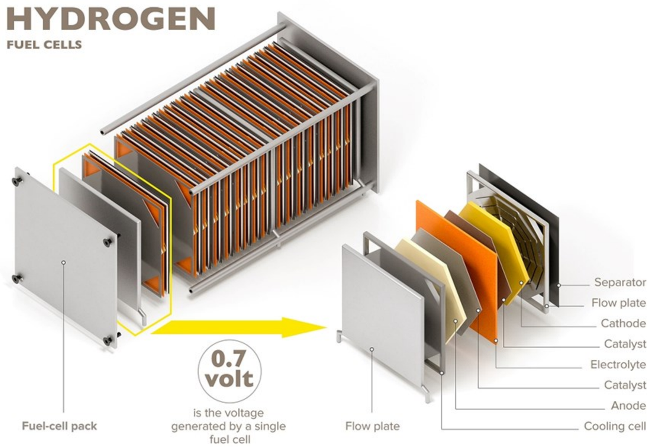
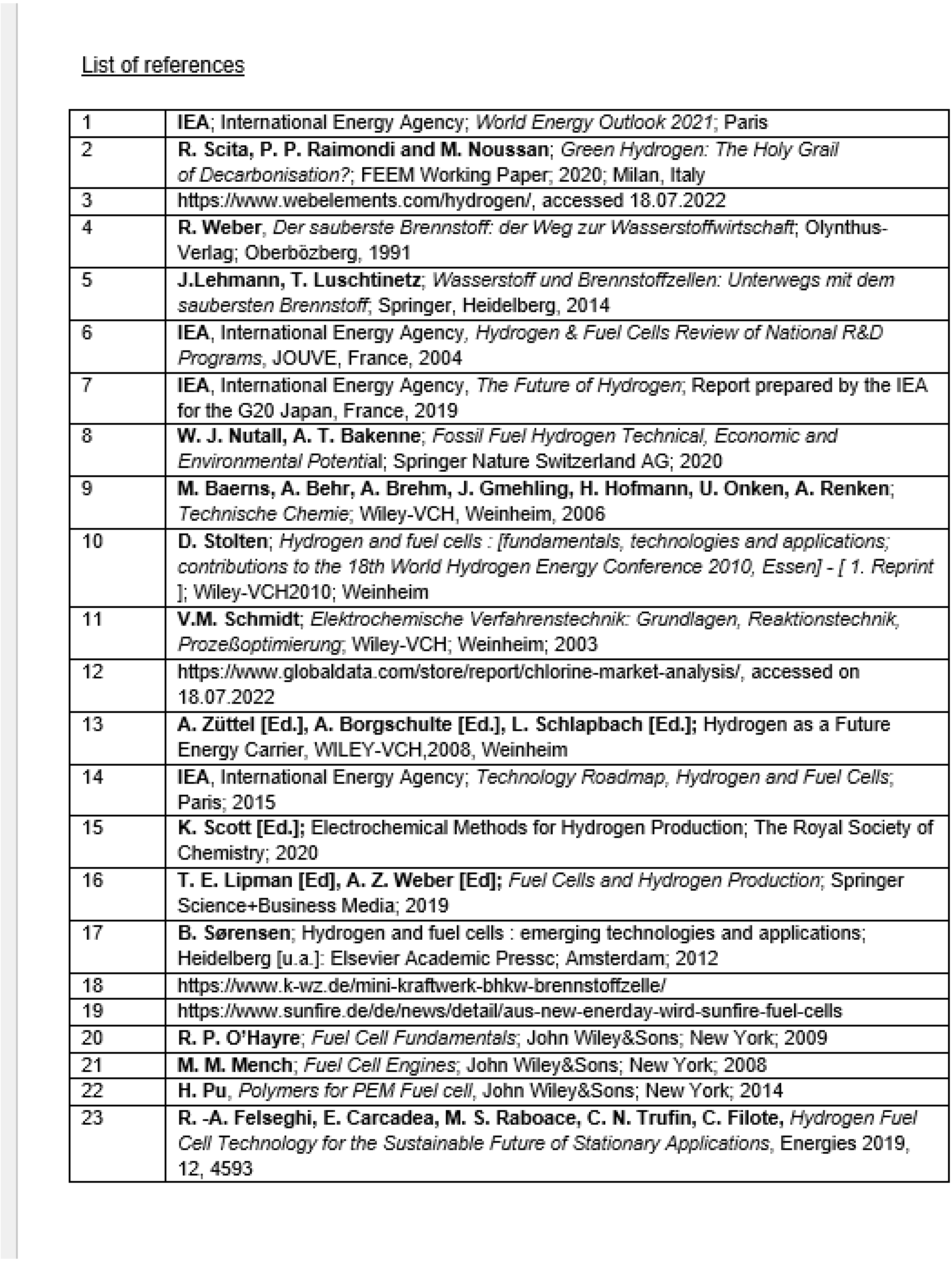


Figure 18: Fuel cell stack

In addition to the popular option of operating fuel cell (stacks) with hydrogen, other types of fuel cells differ in the underlying reaction and the process parameters. In Table 8 you can see a summary of the different technical possibilities:

Table 8: Comparison of different fuel cell technologies [20,22,23]

Type of fuel cell	Electrolyte	Typical power range	Temperature	Efficiency	Reduction-agent	Oxidation-agent	Pros	Cons
Polymer Electrolyte Membrane (PEM)	PTFE PEEK sPi	<1 KW – 100 kW	<120 °C	40-60 %	H_2, C_2H_5OH, CH_3OH	O_2	Solid electrolyte, low corrosion electrolyte, management easy, faster start-up time	Expensive catalyst; high purity of the fuel required
Alkaline Fuel cell (AFC)	KOH	1 – 100 kW	60-250 °C	>60 %	H_2	O_2	High efficiency; low material requirements, low cost	Pure oxygen is needed, no CO_2 contaminations
Phosphoric acid fuel cell (PAFC)	Phosphoric acid in porous material	5 – 400 kW	150-200 °C	40 %	H_2	O_2	Suitable for combined heat and power; high tolerance of the educt purity	combined heat and power only with pure fuel
Molten carbonate fuel cell (MCFC)	molten Li, Na or K - carbonate	300 kW – 3 MW	600-700 °C	50 %	H_2	O_2	High efficiency; low requirements for the purity of the starting materials; Suitable for combined heat and power	High temperature, high corrosion, requirements on the components are very high
Solid oxid fuel cell (SOFC)	Yttria stabilized zirconia	1 kW – 2 MW	500-1000 °C	60 %	H_2, CO	O_2	High efficiency, flexible types of fuels; solid electrolyte; Suitable for combined heat and power	High temperature, high corrosion; very high requirements on the components; long boot time, limited number of restarts



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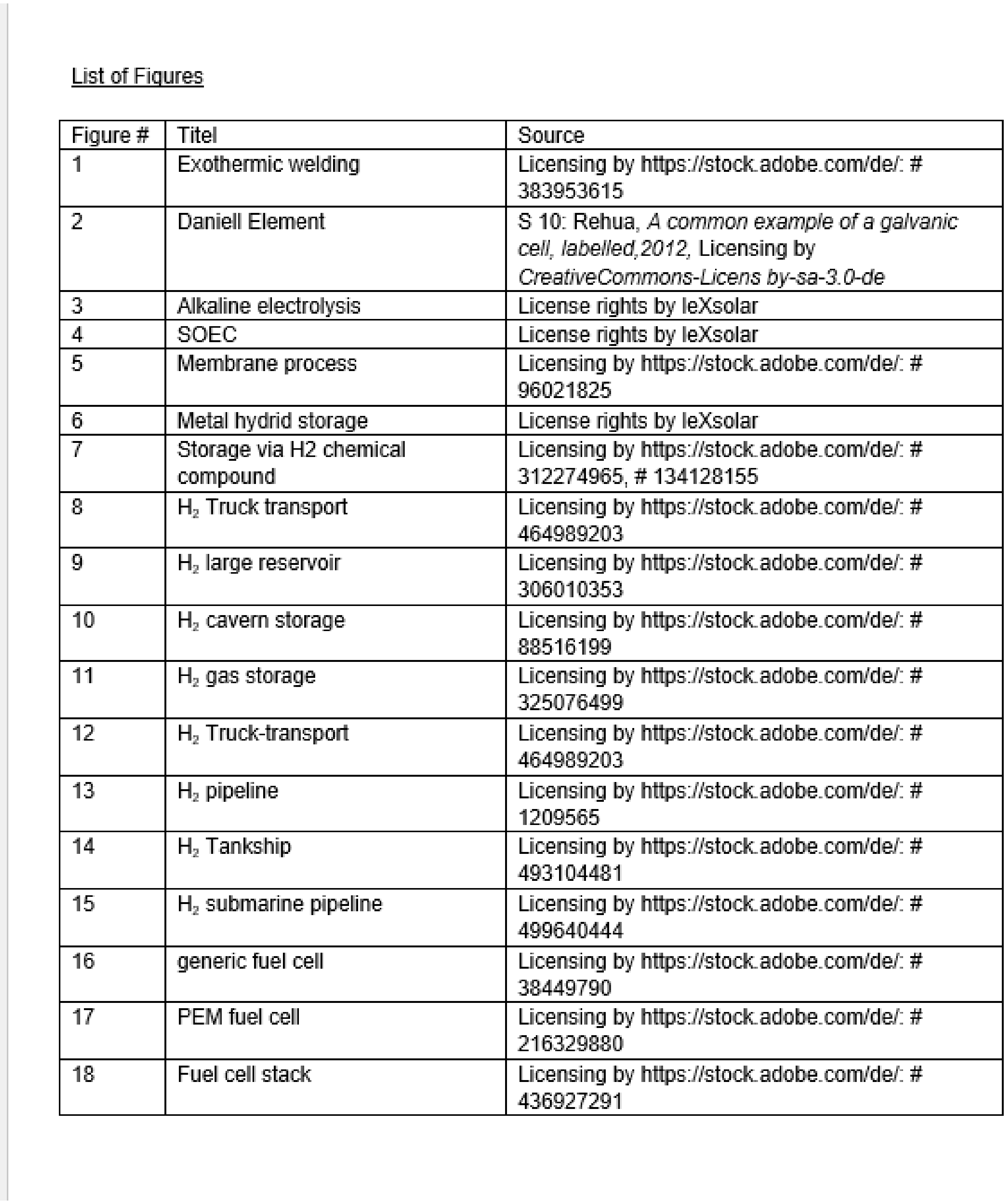

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2	Daniell Element	S 10: Rehua, *A common example of a galvanic cell, labelled,2012,* Licensing by *CreativeCommons-Licens by-sa-3.0-de*
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7	Storage via H2 chemical compound	Licensing by https://stock.adobe.com/de/: # 312274965, # 134128155
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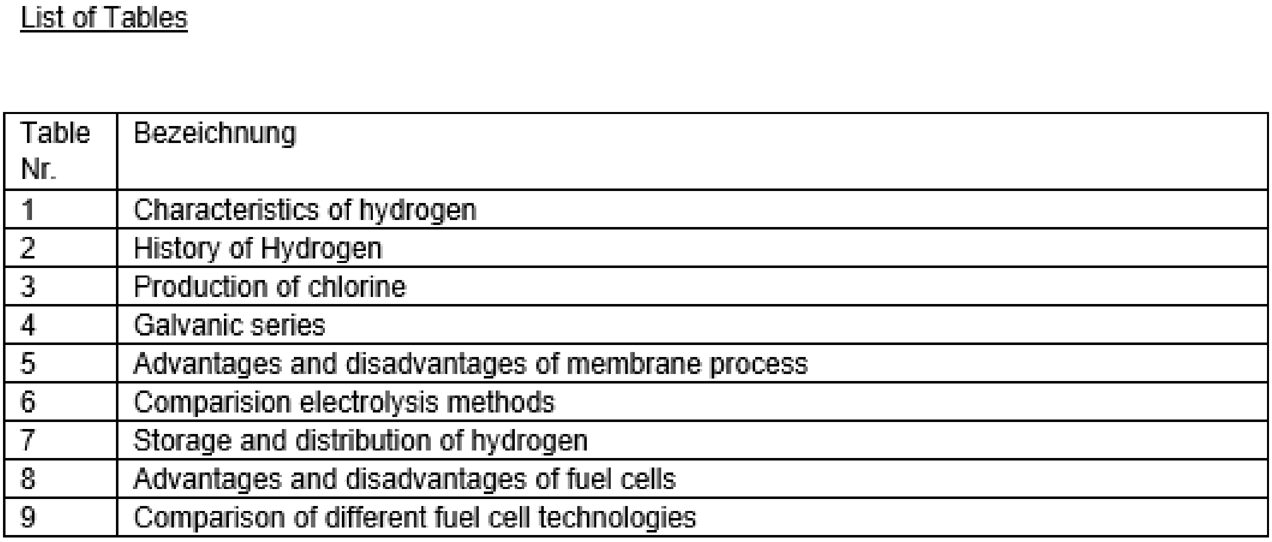
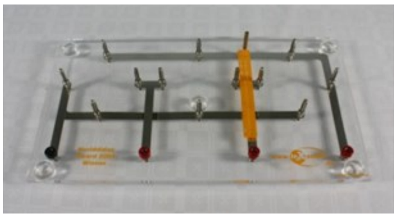
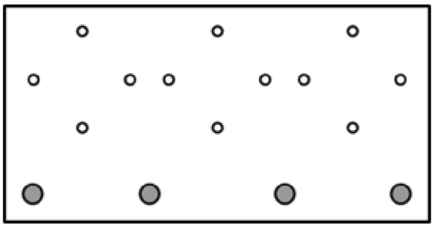
17	PEM fuel cell	Licensing by https://stock.adobe.com/de/: # 216329880
18	Fuel cell stack	Licensing by https://stock.adobe.com/de/: # 436927291



List of Tables

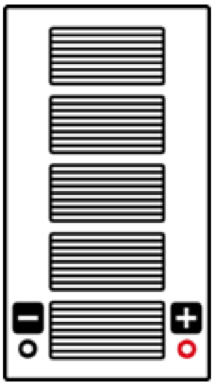
Base unit 1100-19





The base unit is a breadboard where up to 3 components can be plugged in a series and parallel connection. The current flows along the wires on the bottom side. To connect the components on the base unit with other components, there are 4 terminals at the lower end.
The printed circuit diagram show the connections in a series and parallel connection. To change between series and parallel connection, the modules have to be turned by 90°.

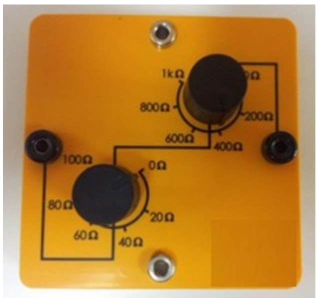
Solar module, large 1100-31 2,5V 420 mA

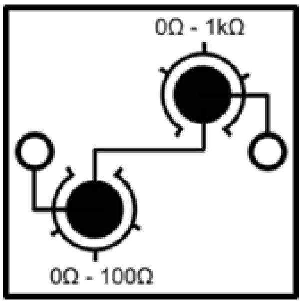


This solar module is a serial connection of five solar cells.

Specifications:
Material: polycristalline silicon
Open circuit voltage: 2,5V
Short circuit current: 420mA
Maximum power: 1Wp

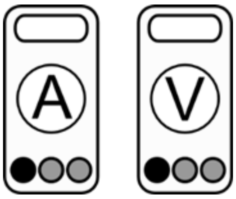
Potentiometer module 1100-23





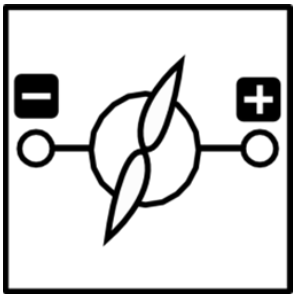
The potentiometer module holds a 0-100-Ω-potentiometer and a 0-1-kΩ-potentiometer. Both are serially connected, so that the potentiometer can attain resistances between 0 Ω bis 1100 Ω. The measuring error amounts to 5 Ω for the small resistor and 20 Ω at other one. The maximum current amounts to 190 mA.

Digital multimeter L2-06-011



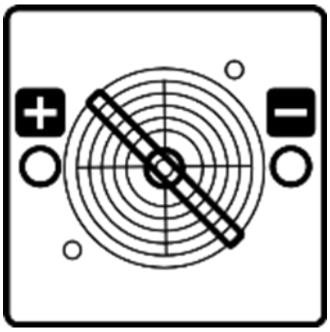
The multimeter is able to measure alternating and direct voltage, current and resistances with the supplied cables. For the use, turn the knob to the desired measuring range. The unit can be read at the inscription. Ordinarily, connect the two cables at the left jacks. In case of higher currents than 250mA, use both external jacks. Otherwise, a fuse will be destroy and it is no longer possible to measure the current with the left jacks. Exchange the fuse by unscrewing the casing on the back side.

Motor module (1100-27) with yellow propeller (L2-02-017)



The motor module acts as a consumer in the H_2 experiments.

Solid Oxide Fuel Cell (SOFC) module 1218-01

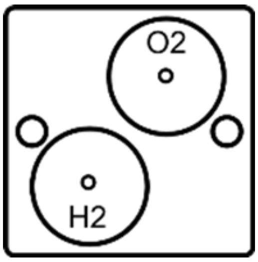


Direct flame microtubular solid oxide fuel cell that uses a gaseous fuel (propane-butane mixture) which is beneficial to small-scale power generation and, therefore, can be safely used in the classroom.

Gas burner small L2-06-133

Use the gas burner to heat the SOFC

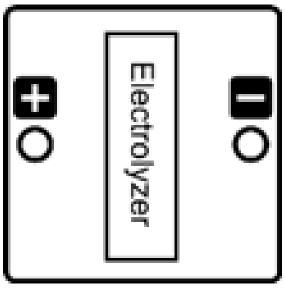
Gas Storage module 1213-01



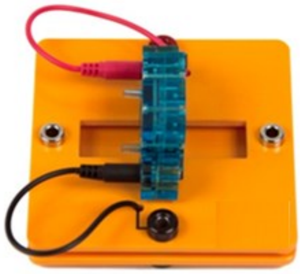
Introduction

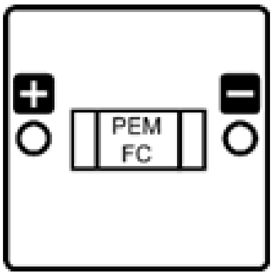
Components

Electrolyser module 2.0 1218-03

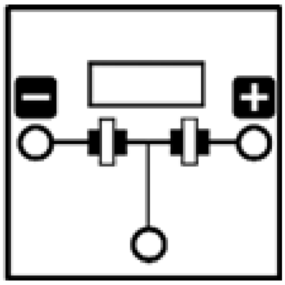


PEM fuel cell module 1218-02





Ethanol fuel cell module 1700-01



Lamp with table clamp L2-04-022

Introduction

Components

Test leads

2 x L2-06-012/ 013 Test lead black/ red 25 cm
1 x L2-06-014/ 015 Test lead black/ red 50 cm
1 x L2-06-002/ 003 Test lead black/ red 25 cm, 2mm plug

Optional Component H2 Charger 1200-17

H2 Storage + valve for h2 storage L2-06-132

Introduction

Operations of the electrolyser

Specifications:

Input voltage: 1.8 V ~ 3 V (D.C.)
Input current: -0.7 A
Hydrogen production rate: 7 ml per minute at 1 A
Oxygen production rate: 3,5 ml per minute at 1 A

Important handling guidelines:

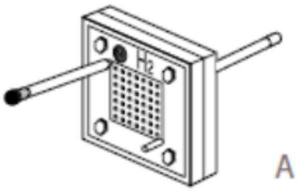
Whenever not in use, the electrolyser should be stored in an air-tight plastic bag, to keep it from drying out.

Positive and negative pin of the electrolyser must always be connected to correctly to the voltage source, to avoid damages to the electrolyser.

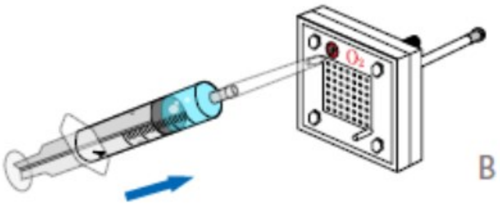
The electrolyser must only be used with moistened membranes. The distilled water must be filled in on the O_2-side and should be allowed to soak for about 3 minutes. Connecting the dry electrolyser to the voltage source can lead to irreparable damages.

User instructions:

1. The electrolyser should be placed on a flat surface. The short piece of tube must be connected to the upper port on the H_2-side (black port) and be sealed with the black pin (see A).

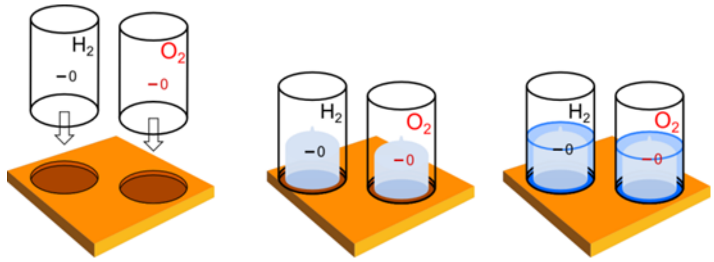


2. The syringe must be filled with distilled water and another short piece of tube should be fitted to it. The other end of the tube must be connected to the upper port on the O_2-side (red port) (see B).



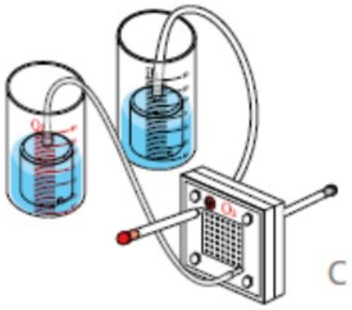
Now, using the syringe, the water should slowly be pumped into the electrolyser until it leaks out of the lower port. The syringe can now be pulled off the tube, which can be sealed with the red pin. At this point the electrolyser should sit for 3 minutes.

3. Now, the water barrels should be filled with distilled water up to their respective markings.



4. Each gas storage tank should be pinned onto the ring mount at the bottom of each water barrel, so that the grooves on the bottom of the gas tanks are aligned with the grooves of the ring mounts. Excess water can be removed using the syringe.

5. At this point, the gas storage tanks can be connected to the lower ports of the electrolyser using the long pieces of tube. The black port of the H_2-side must be connected to the H_2- storage tank and the same goes for the red O_2-side and the O_2 tank (see C).



6. The electrolyser can now be placed onto the module plate and be connected to it using the respective cables (red for O_2, black for H_2).

7. Now, the unit can be connected to the solar module or an external voltage source to start the electrolytic process.

NOTE: If the hydrogen gas shall later be used for a fuel cell experiment, it is recommended to put a clamp on the tube connecting the H_2-side of the electrolyser with the H_2 tank. It can be closed after the gas production, so that the hydrogen can be stored in its tank for later experiments.

Specifications:

Output power: 270 mW
Output voltage: 0,6 V (DC)
Output current: 0,45 A

Important handling guidelines:

Whenever not in use, the fuel cell should be stored in an air-tight plastic bag, to keep it from drying out.

User instructions:

1. To operate the fuel cell, hydrogen gas is needed. This can be obtained from the H_2-Storage or from the H_2 tank from a previous experiment.

2. If the hydrogen is taken from the gas tank, the tube must be clamped to avoid hydrogen gas to leak.

3. The tube of the H_2 tank must be connected to the lower port of the fuel cell. The O_2 supply for this model is ensured by the ambient air.

4. The upper port of the fuel cell must be sealed, using a short piece of tube and a pin.

5. The fuel cell can now be placed onto the module plate and be connected to it using the respective cables (red for O_2, black for H_2).

6. Now, the unit can be connected to an electrical load. (Mind the polarity!).

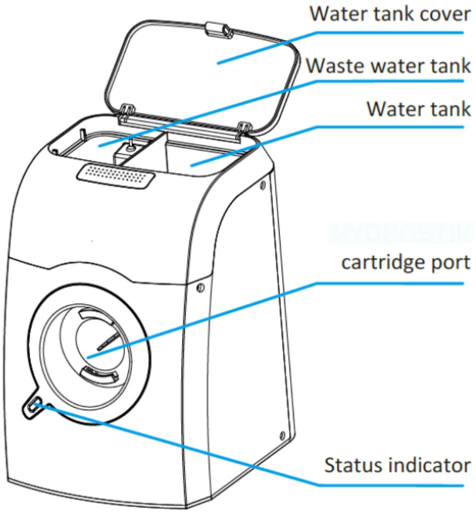
7. By opening the tube clamp the experiment can be started.

NOTE: For quantitative experiments like taking a characteristic curve, we recommend flushing the fuel cell with hydrogen gas by initiation the gas supply (opening the tube clamp on the tank or opening the valve on the H_2 storage) and removing the pin on the short tube for only 1-2 seconds.

Introduction

Operations components
H2 Charger and H2 Storage

Designation of the parts:



Specifications H_2-Charger:

- Power: 23 W
- Input voltage: 10 V-19 V (DC)
- Use: De-ionized or distilled water (10-40°C)
- Water consumption: ca. 20 ml/h
- Hydrogen pressure: 0-3 MPa
- Hydrogen production rate: ca. 3 l/h
- Hydrogen purity: 99.99%
- Refill time per cartridge: about 4 h

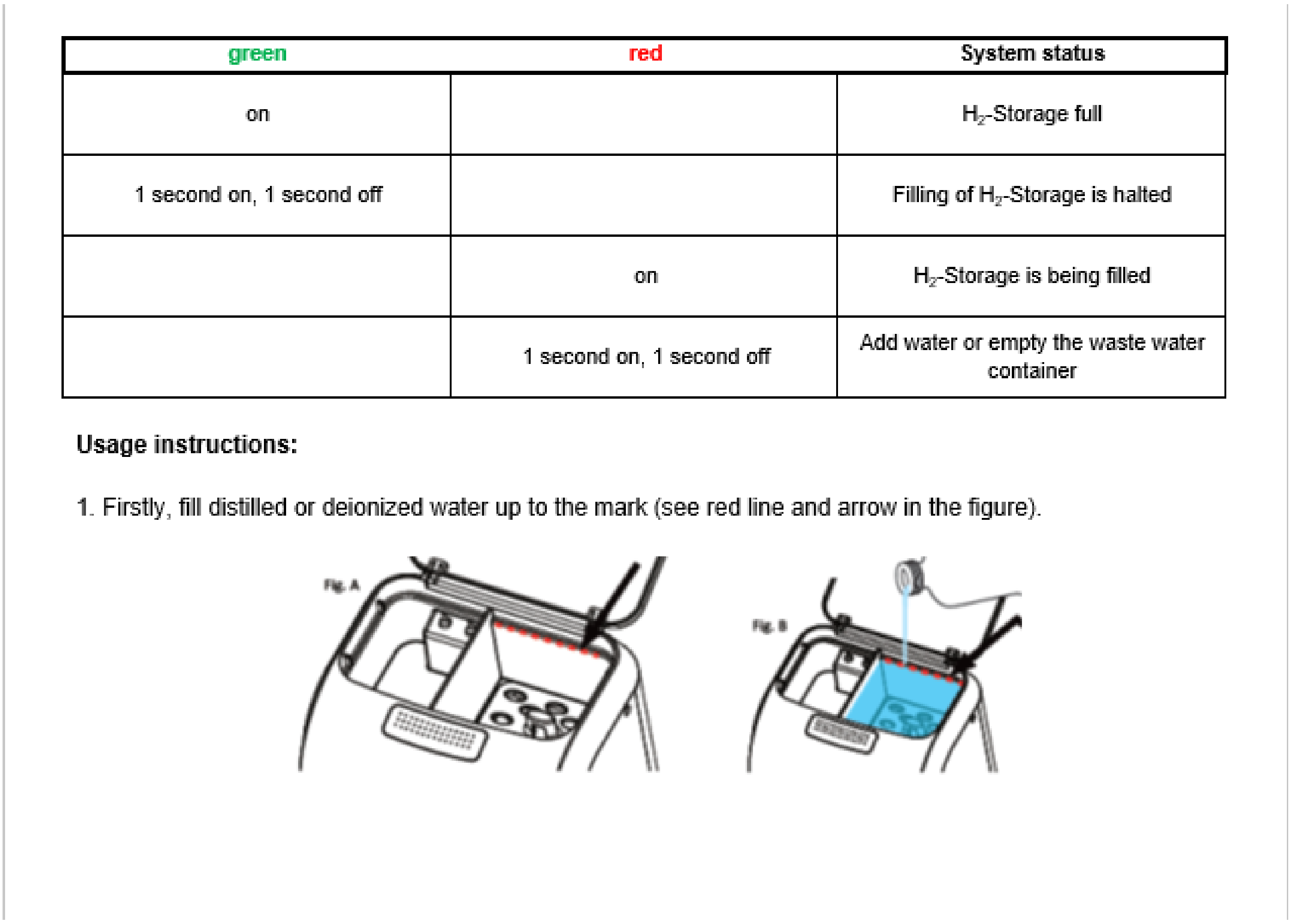
Specifications H_2-Storage:

- Capacity: 10 l hydrogen
- Storage material: AB5 metal hydride
- Load pressure: 3 MPa
- Working temperature: 0-55°C

Important handling guidelines:

The H_2-Charger must not be disassembled.
Both the H_2-Charger and the H_2-Storage must be kept away from heat or flames.
The H_2-Charger should be operated in an upright position.
Operations should be done in a well-vented room.
All electric connections should be kept away from water.

Status light:



green	red	System status
on		H_2-Storage full
1 second on, 1 second off		Filling of H_2-Storage is halted
	on	H_2-Storage is being filled
	1 second on, 1 second off	Add water or empty the waste water container

Usage instructions:

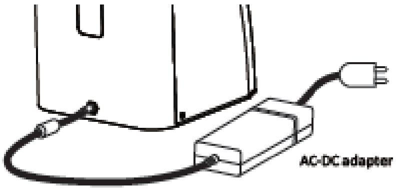
1. Firstly, fill distilled or deionized water up to the mark (see red line and arrow in the figure).

Introduction

Operations components
H2 Charger and H2 Storage

2. Connect the power adaptor to the H_2-Charger. The status light should flash green.

Fig. C



3. Insert the H_2-Storage into the opening on the front side of the H_2-Charger. For this, the stick should be turned clockwise until it locks in place. Don't apply too much force!

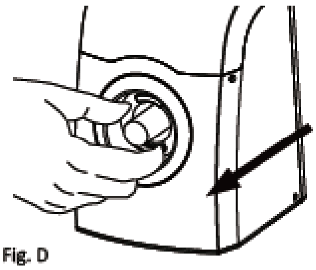
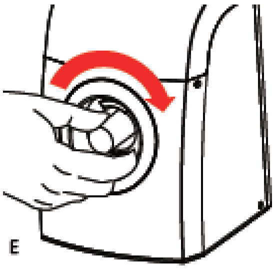


Fig. D



E

4. While the status light is flashing red, the H_2-Storage is being filled. Only when the status light flashes green, the cartridge is completely filled. The stick may now be removed by turning it counter clockwise.

5. Now remove the power adaptor and empty the water tank, in case the H_2-Charger will not be used within the following week. If further cartridges must be filled, revisit this procedure, starting at point 3.

NOTE: Distinct noises (gargling and whistling) are normal during the charging process and are being produced by the self-cleaning of the device.

Introduction

Operation of the SOFC

The operating range of the solid oxide fuel cell starts at 600°C. A gas burner is used to reach this temperature. The flame can reach temperatures up to 1300°C, hence the distance between the flame and the device should be carefully minded.

1. Firstly, the polycarbonate glass element containing the fuel cell and the mount will be connected to the support rod. The support rod can be screwed onto the module plate. The module plate can now be plugged onto the base plate.

2. The gas burner must be placed into the notch of the module plate. The burner has to be centered directly below the fuel cell. During operation, the height of the fuel cell should be adjusted so that the tip of the flame just reaches the lower part of the fuel cell. In this configuration the cell reaches its peak efficiency.

Safety instructions:

For the duration of the experiment and the immediate time afterward, all metal components have to be considered hot. Therefore, users must take care to avoid coming into contact with hot surface.

General instructions:

The solid oxide fuel cell is designed for educational purposes only!
Do not disassemble the fuel cell.
Do not use continuously for more than 5 minutes.
After every experiment wait for 5-10 minutes to cool down the SOFC and fuel cell's housing

Introduction

Safety Indication

General Information

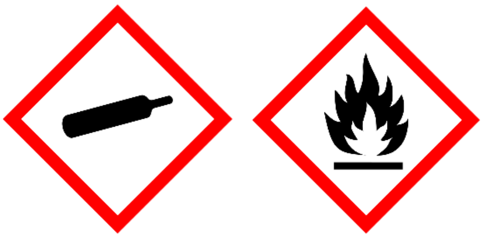
All leXsolar modules should be handled carefully
Pay attention to all local rules and safety concepts
Respect all established safety concepts for handling electric current
All students should be briefed before using leXsolar products and should never experiment alone
It is not permitted to take leXsolar modules apart
If a module is damaged stop experimenting and contact your teacher/supervisor.

H_2 Storage cartridge

The components of the H_2 storage are extremely flammable.
Avoid contact with already damaged parts
Avoid temperatures above 50°C (122°F) or open fire
Keep away from children
Always follow the instruction manual
Separate the H_2 storage from the other parts immediately after finishing the experiments
Charge the H_2 storage cartridge exclusively with the H_2 charger (1200-07)
Do not dispose of as a household waste

Typically, H2 Storage can be recycled where rechargeable batteries are recycled. Recycle Procedures: The materials in the H2 Storage are 100% recyclable, and so in order to get the H2 Storage metal hydride cartridges recycled properly, return the cartridge to your local outlet or distributer. Normal Disposal Procedures: The H2 Storage metal hydride cartridge does not contain any dangerous substances for the environment, we would recommend that they still be disposed of in a similar way you would dispose of a standard battery.

Hydrogen



H220	Flammable gas.
H280	Contains gas under pressure; may explode if heated
P210	Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking.
P377	Leaking gas fire – do not extinguish unless leak can be stopped safely.
P381	Eliminate all ignition sources if safe to do so.
P403	Store in a well-ventilated place.

Oxygen

H270	May cause or intensify fire; oxidizer
H280	Contains gas under pressure; may explode if heated
P244	Keep valves and fittings free from oil and grease.
P220	Keep/Store away from clothing/.../combustible materials.
P370 +376	In case of fire: Stop leak if safe to do so.
P403	Store in a well-ventilated place.

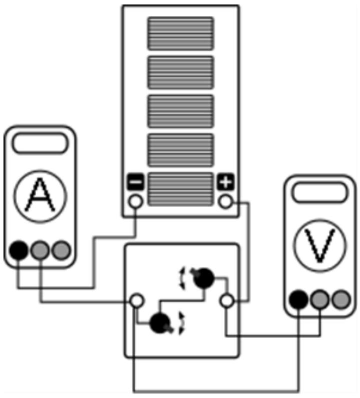
Worksheet

I-V curve of a solar module

Task

Take the I-V curve of a solar module and interpret its behavior.

Setup



Required Equipment

Solar module
Lamp
Cables
Ammeter
Voltmeter
Potentiometer module

Procedure

1. Set up the experiment in accordance with the drawing.
2. Place the lamp in front of the solar module (distance ca. 30 cm) and switch on the lamp.
3. Set sensible values for the voltage and measure the resulting current. For this, first adjust the 1kΩ resistor and then the 100Ω resistor for better control.
4. Enter your measurements into the table.

Measurements

V in V	I in mA	P in mW

Worksheet

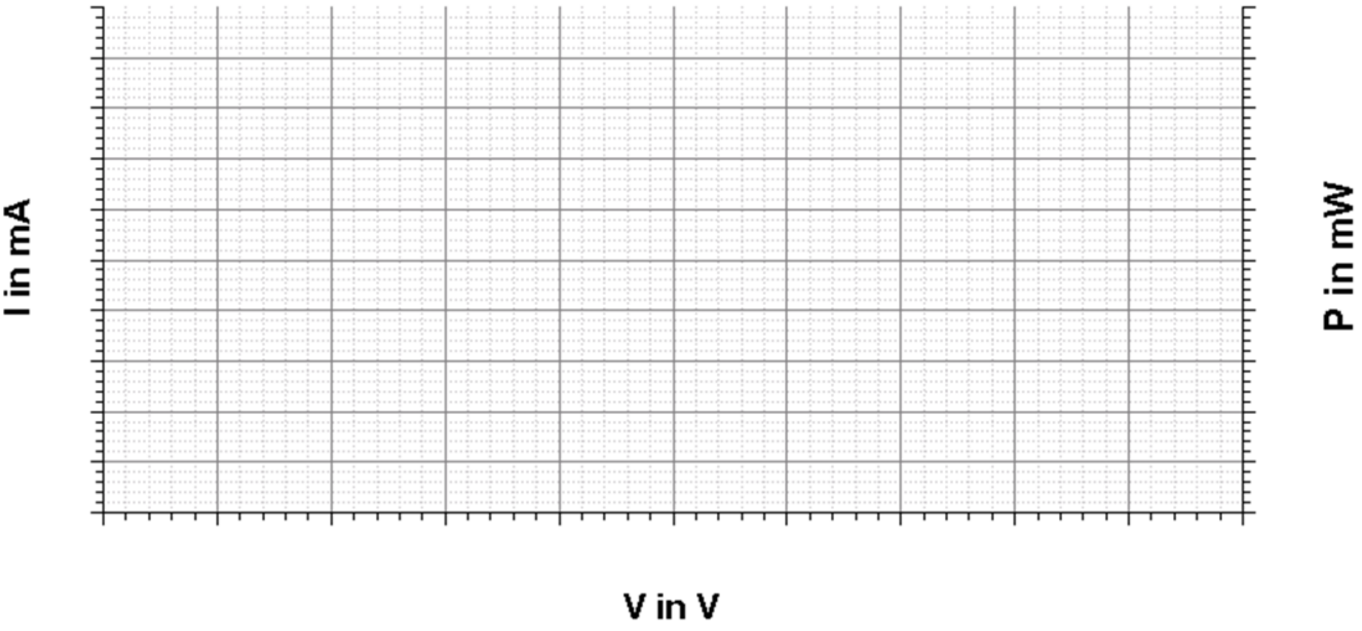
I-V curve of a solar module

Evaluation

1. Calculate the power for every pair of voltage and current values and enter your results into the table.
2. Plot the respective value in the given diagram.
3. Describe the behavior of the current and the power in dependence of the voltage.

Diagrams

2.



3.

The full version of this curriculum is available upon purchase of the kit.

Please see contents for a full list of experiments from the full version.