HYDROGEN

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1. THE CLIMATE CHANGES DAILY!

Agricultural land for food, electricity and gas for houses, fuel to get from A to B: we need more space and energy than the earth can handle. This results **in climate change**.

The earth is warming up and this is changing our climate. This is not a new phenomenon because there have been ice ages and warm periods with consequences for life on earth.

It is now on average more than 1 degree warmer worldwide than in the period 1850 - 1900. The consequences for nature and the disadvantages of climate change are already visible. With further warming, the consequences will become more serious.

Climate researchers worldwide always come to the same conclusion: humans are responsible for global warming. Human activities release greenhouse gases. Natural processes - such as changes in the activity of the sun and volcanic eruptions - hardly play a role in global warming.

The warmer it gets, the more disastrous the consequences. Every 0.1 degrees counts for the future. The current warming of more than 1 degree can no longer be reversed. But warming above 1.5 or 2 degrees can still be prevented. So there is hope, because if we succeed in limiting further warming, the adverse effects will be less.

For a maximum of 2 degrees, global CO2 emissions should start to fall rapidly and be zero well before the end of this century, for a maximum of 1.5 degrees to zero about halfway through this century. In addition, it is necessary to remove CO2 from the atmosphere and capture it. Emissions of greenhouse gases other than CO_2 must also be greatly curtailed. Rapid and drastic action is needed from governments, businesses and consumers.

More information about climate change?
Follow the link and discover a performance by paleologist Mei Nelissen at work at the University of the Netherlands

1.1 What is the greenhouse effect?

Greenhouse **gases** such as CO_2 occur naturally in the atmosphere. That's a good thing, because otherwise it would be much colder on Earth. Greenhouse gases ensure that the heat of the sun is retained.

Without greenhouse gases, it would be -18 degrees Celsius on average here. Due to the greenhouse gases, it is an average of 15 degrees Celsius, making life on earth possible.

In the last 250 years, many more greenhouse gases have been released into the atmosphere. They retain extra heat, which has caused the temperature to rise for 140 years: the enhanced greenhouse effect.'

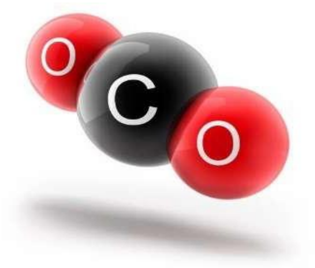
People popularly speak of "the greenhouse effect" but actually they mean "the extra greenhouse effect".

Humans are the main cause of global warming. Since the industrial revolution, we have been emitting more and more greenhouse gases.

We use fossil fuels in factories, power plants,... to heat our homes and for transport. In addition, we are cutting down more and more forests and increasing livestock numbers, which also releases extra CO_2.

The most important greenhouse gases are: carbon dioxide, methane, nitrous oxide and water vapor.

CO_2 is the abbreviation for **carbon dioxide** and amplifies almost 50% of the additional greenhouse gases. Another name is carbon dioxide. The two main sources of CO_2 are fossil fuels and land use change.

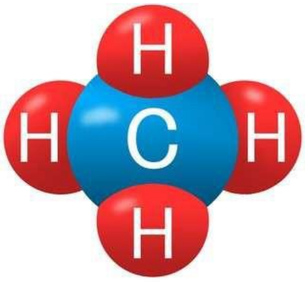


In early geological epochs, carbon dioxide was sequestered by trees and other organisms. Fossil fuels (oil, coal, natural gas) were eventually formed from this. When these fossil fuels are burned, the CO_2 is released again.

In addition to emissions from fossil fuels, land use change also causes CO_2 emissions. Deforestation takes place to make room for agricultural land. In this process, the CO_2 that is captured in the wood ends up in the air. Peat soils can also release CO_2 when they dry up because they contain large amounts of plant debris, which can be converted into CO_2 if the water level drops too much.

Follow the link and discover changes in CO_2 concentration in 2021.
The colors are the measure of concentration: red = high and blue = low.
Discuss the case below.

In the animation, the influence of weather change and the slow seasonal cycle of plant growth is clearly noticeable. What do we see during the summer and winter? What evolution do we see around industrial areas?



The colourless **methane** with the chemical name CH4 is mainly released in livestock farming.

Cows, sheep and goats produce methane when digesting food. That methane comes into the air through their breath, burps and farts. Methane is also released during the cultivation of rice and from landfills.

Methane is a strong greenhouse gas: 1 kilo of methane has the same effect as 28 kilos of CO2.

Nitrous oxide is known in the chemical world by the chemical name N2O or nitrous oxide. It is mainly released from soil that has been fertilized with artificial fertilizer or animal manure. Nitrous oxide is a very strong greenhouse gas: 1 kilo of nitrous oxide has the same effect as 265 kilos of CO2.

Water vapor is also a greenhouse gas. Global warming is making the air warmer, and warm air can contain more water vapor. Because water vapor is a greenhouse gas, that extra water vapor in the air causes more warming, which can cause the air to contain even more water vapor, which warms the earth even further and so on. In this way, the greenhouse effect of water vapor reinforces itself. People cannot do anything to control the amount of water vapor in the air.

Fluorine gases are the strongest greenhouse gases on earth: they can cause thousands of times as much warming as CO2. Well-known fluorine gases are HFCs and PFCs that can occur in aerosols, air conditioners and refrigerators, among other things. The most powerful fluorine gas is SF6, which is used as an insulating gas in the electricity grid. SF6 causes 22,800 times as much warming as CO2.

Last century, agreements were made to prevent the release of these kinds of strong greenhouse gases. Yet fluorine gases still end up in the air, for example if refrigerators and air conditioners are not replaced by energy-efficient ones. To prevent fluorine gases from leaking out, governments are developing increasingly strict rules.

What can we do for the climate ourselves in the short term? **Less CO2 emissions**!

1.2 Calculate your carbon footprint

Do you have a lot of impact on the earth? On average, we use much more than is actually possible, making a fair distribution unthinkable.

By calculating our ecological footprint, we can see how many hectares of the earth people use personally.

With a fair distribution, there would be 1.8 hectares or 3 football fields of space available per person on our globe.

Worldwide, however, we now use an average of 2.7 hectares per person. As a Belgian, this figure is even higher = about 4 hectares... In this way, the earth is slowly becoming exhausted.

Calculating the exact ecological footprint is quite complicated and depends on various factors such as our food, lifestyle, place of residence,...

There are various tests on the internet to get an estimate of your personal ecological footprint.

How sustainable is your lifestyle? Follow the link and take the test prepared by the World Wide Fund for Nature.

Shocked by the result? How do you plan to reduce your footprint in the short term?

In the past, people lived differently than they do now. Nowadays, people have different needs and requirements: faster, simpler, more powerful, better for the environment,... This is also noticeable in the evolution of means of transport, machines,... Everything works with **a technical system** in which different parts work together and will fulfill an essential task.

2. TECHNOLOGY EVOLVES

We also see this in the development of the bicycle over the past 200 years. In 1817, Baron Karl von Drais designed **a balance bike**. From 1860 onwards, the development of a bicycle with **pedals and a rotating bottom bracket** in the front wheel gained momentum. Later, **the bicycle chain** was introduced and the models were adapted according to the circumstances: city bikes, sports bikes,...

By using gear devices, the bike is now suitable for any terrain. And if you don't have the right gear or condition, there is an extra tool available when cycling: **electricity**.

We see this aid not only on the bike but also on most technical systems around us.

Karl von Drais' balance bike

More information about mounting a bicycle? Follow the link!

A technical system consists of **3 parts**:

IMPORT = INPUT	PROCESSING	EXPORT = OUTPUT

We also call this system **an IPE process**.

To make a technical system work, you also need information, matter and energy. Electricity is usually used as an energy source. This energy will be converted into **another form**. The operation of a coffee machine makes this clearer, whereby **a thermal energy** will be generated.

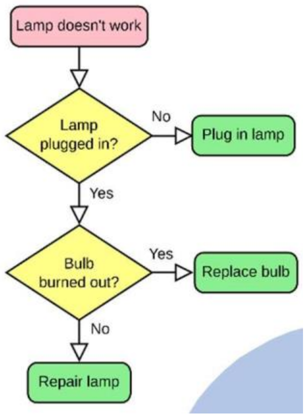
INPUT	PROCESSING	OUTPUT
Energy = electricity	Converting electricity into heat	Warmth
	Boiling water	Heat for the coffee
	Keeping coffee warm	Heat for the hot plate

Electricity can also be converted into **kinetic energy** , such as with a drill, pump,... Keep in mind that electricity is a secondary source of energy. One needs a primary energy source to generate electricity.

The operation of a technical system can be read in **a flowchart**. This is a diagram in which all parts of the process are placed **in the correct order** with intermediate arrows.
Rounded rectangles indicate the beginning and the end. The rectangles show the different actions.

For the **diamond shapes**, conditions are filled in where the answers can be yes or no.

In the example we see the flowchart of a defective lamp.



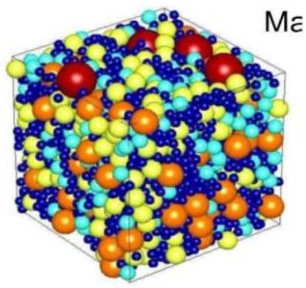
A battery-powered electric drill driver does not work. Draw a flowchart with the different actions to make the device work correctly. Use the right shapes.

3. ELECTRICITY MAKES OUR LIVES EASIER

If one wants to understand the concept of electricity, we have to look at the materials around us. A material is a raw material that is needed to make a product such as a sheet of aluminium, a roll of copper wire, a gas cylinder,... All these materials consist of **a matter**. And we see that all around us!

Some examples: a table, a water glass, the water one drinks, a cloud, a spanner,... Everything that has a mass and needs space is a matter.

The air that one breathes is also matter. People do see right through it and don't seem to weigh anything... Yet it is not so. Everything around us is made up of very small particles that have a very small mass. These particles are called **atoms**.



These atoms sit together in a special way, creating a structure: the molecules. People who study this are called chemists. They look at the properties of the substances, how they react with other substances,... They will then incorporate this into various laws that will be used in industry, among other things.

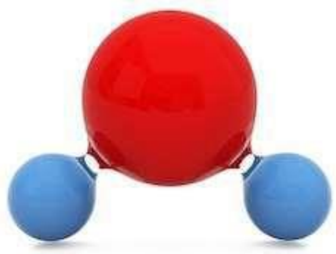
The word chemistry also contains the word separation. An example is coffee with milk and sugar. We could separate this into different substances such as water, milk, coffee powder and sugar.

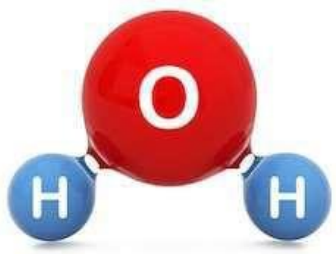
A chemist goes one step further because he will be able to split the water further! Water consists of 2 chemical elements: hydrogen atoms and oxygen atoms. These elements cannot be split further and will therefore be given their own letter that refers to the Latin name.

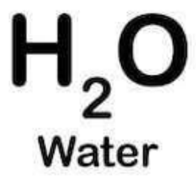
ATOM	LETTER	LATIN NAME
Hydrogen		
Oxygen		

A chemist or chemist can also combine different substances to create a new matter: synthesise. Usually one will work in a laboratory where one uses a common chemical language . The chemical name for water is H2O.

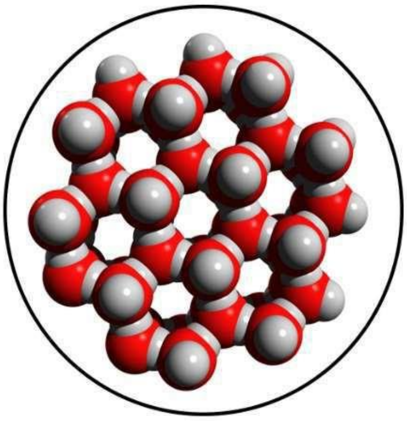
Chemists have discovered that water consists of 2 atoms of hydrogen and 1 atom of oxygen.

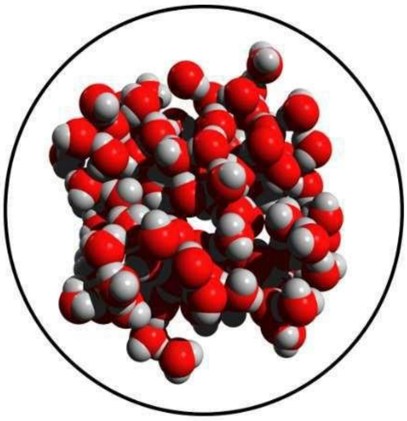


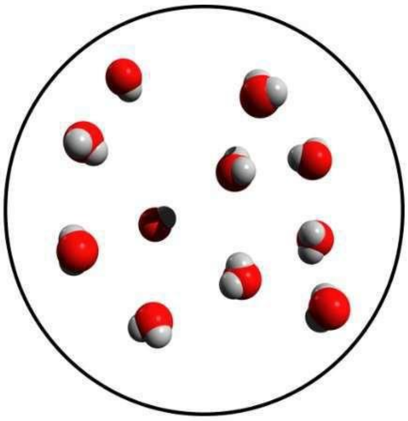




Water can also come in different forms: liquid, gaseous or in a solid state. The structure will be different each time.







LIQUID	SOLID	GASEOUS

3.1 Is an atom the smallest particle?

In the past, people were rich if they had a lot of **gold** . People went looking for it in nature and when they had found it, they spoke of **a gold nugget**. Such a lump can be further divided into **smaller pieces** where the properties will always remain the same. Gold is therefore an atom with **a chemical name**.

ATOM	LETTER	LATIN NAME
Gold	Au	Aurum

An atom is the smallest particle of a chemical element that still retains all the properties of that element. They are therefore the building blocks of everything that can be found on **earth**.

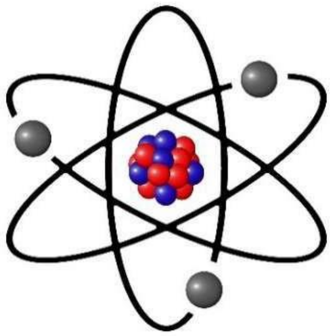
Atoms are so small (= about 100 picometers) that they can only be viewed with **a special microscope**! When billions of atoms are together, they only become visible. In nature, 90 different atoms or chemical elements occur.

In addition, chemists in a laboratory have developed more than 25 other types of atoms. Every day they work on discovering and compiling new elements.

In the meantime, it has also been discovered that atoms can be **further split** into smaller particles, some of which have an electric charge:

PROTONS	NEUTRONS	ELECTRONS
Positive electric charge	No charge	Negative charge

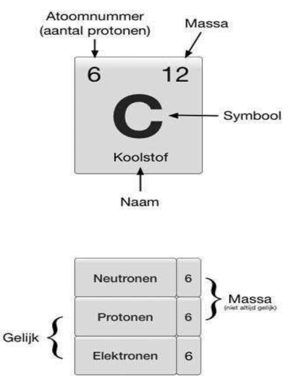
A further splitting will cause the atom to lose its properties.

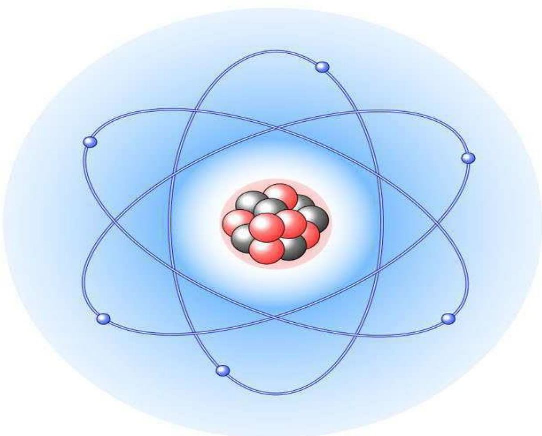


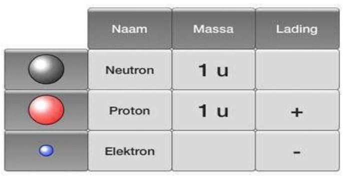
An atom consists of **a nucleus** in which **the protons and neutrons** are close together. Every atom has a number or number: these are the number of protons in the nucleus. We call this **the atomic number** or **atomic number**. If we add up the number of protons and neutrons, we get **the atomic mass**.

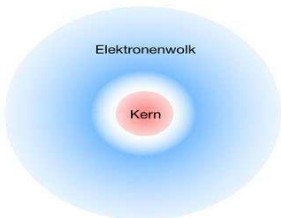
Around the nucleus, **electrons fly** around according to **a certain orbit** or **electron shell**. We can compare this to the planets that orbit the Sun. The number of electrons and protons will be **equal**, so the charge of an atom will be zero.

All those elements with their atomic number were tested by a Russian chemist **Dmitri Mendeleev** in a table. We are talking about **Mendeleev's table**.







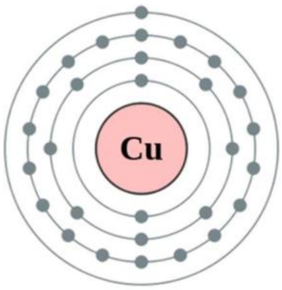


ATOM	LETTER	ATOMIC NUMBER	LATIN NAME
Carbon			

*Search the internet for Mendeleev's table and complete the information about the various **chemical elements** . Please note: there is a difference between **uppercase and lowercase letters!***

ATOM	LETTER	NUMBER	ATOM	LETTER	NUMBER
Nitrogen			Sodium		
Magnesium			Aluminium		
Chlorine				Ca	
Vanadium			Chromium		
Iron			Nickel		
Radium			Zinc		
Platinum				Ag	
		29	Tungsten		
	Pu		Mercury		

3.2 What is an electric current?

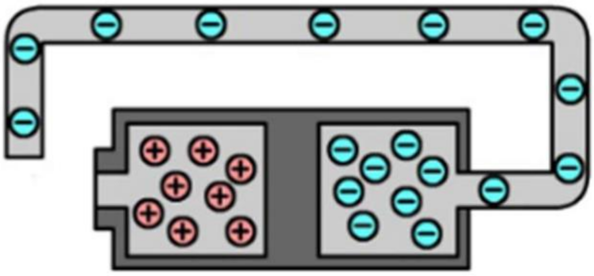


Because electrons flow through an electrical wire like water in a garden hose, people often speak of **current** instead of electricity. Another word used is **tension**. These 2 words do not have the same meaning or function: a socket has voltage that allows a current to flow through a consumer.

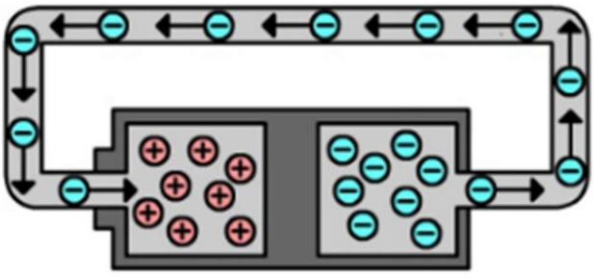
To understand the concept of current, we start with the **free electrons** that are not stuck in an atom or can be released. In a metal, the atoms are arranged in **a lattice** where there is **enough space** to move between them. A material that is often used in electrical cables is **copper**. Each copper atom has 1 free electron with **a negative charge**.

The movement of charge is called **electricity**. To generate electricity, one needs **a voltage source** . This is an object of which 1 part has a surplus of negative charges = **the negative pole**. The other part has a surplus of positive charges = **the positive pole**. A battery, a socket and alternator are sources of voltage.

If you connect the 2 poles with each other, the negative charges will flow to the positive pole. The positive charges do not move because they are stuck in the atomic nuclei. This is called **a closed circuit**.

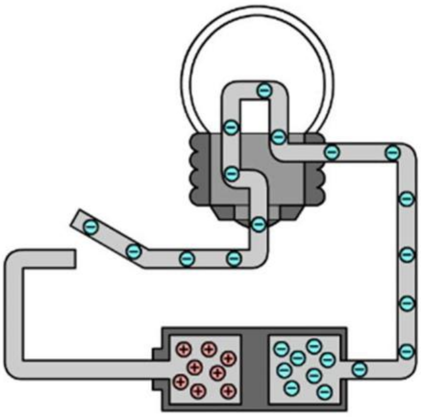


Open circuit

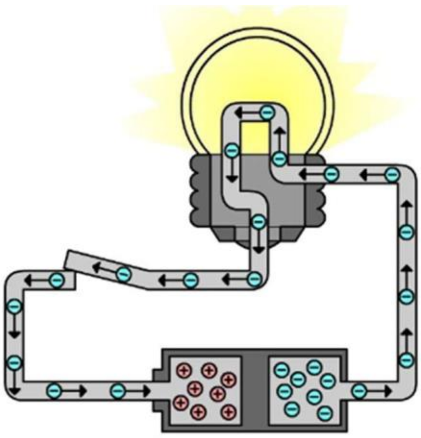


Closed circuit

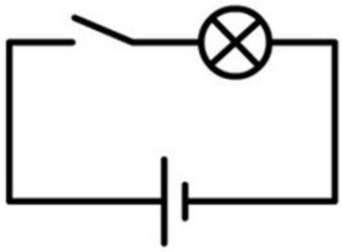
A switch **and** a lamp **can also be added to the circuit**. A switch is no more than a valve with which the circuit can be closed or opened. These parts will be represented schematically with standardized symbols.



Open circuit

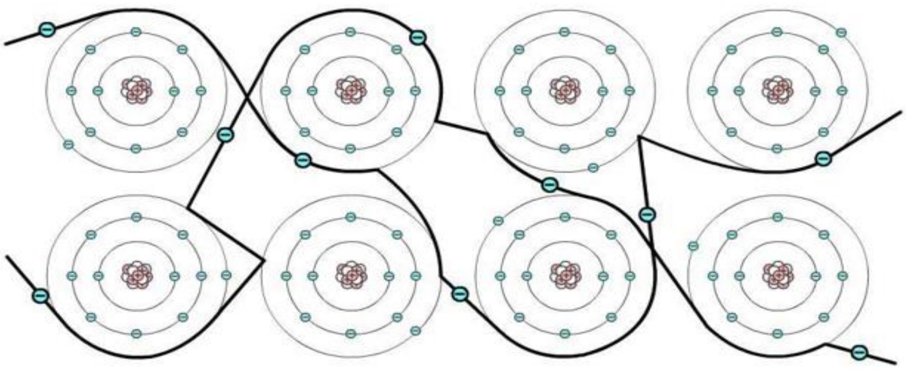


Closed circuit



Simple schematic representation

In addition to the current of the electrons (= actual current sense), one also speaks of **a conventional current sense** outside the voltage source. This runs **from plus to minus**! As the charges flow through a circuit, they constantly **collide** with the atoms that make up the wiring. In a filament of a lamp, these collisions are sufficient to heat the filament in such a way that it starts to glow and start to emit light = incandescent bulb.



Schematic representation of electrons colliding with an electric current

bulb

The difficulty with which a material allows charges to pass through is called the resistance. **Conductors** are materials

with a small resistance such as metals and will be used for wiring in electrical circuits.
Materials with a high resistance are **insulators** such as plastic and wood. The electrons cannot move freely here! Electrical cables in a circuit consist of a combination of conductors and insulators to guarantee **safety**.

More information about the link between atoms and electricity? Follow the link

4. GENERATING ELECTRICITY

There are several ways in which electricity is generated today. In the past, electricity was only generated in power plants, nowadays it is also generated in **a sustainable way**. People usually talk about 2 types of electricity: **green** and **gray electricity**. Green electricity is generated in a nature-friendly way and comes from **sustainable energy sources**.

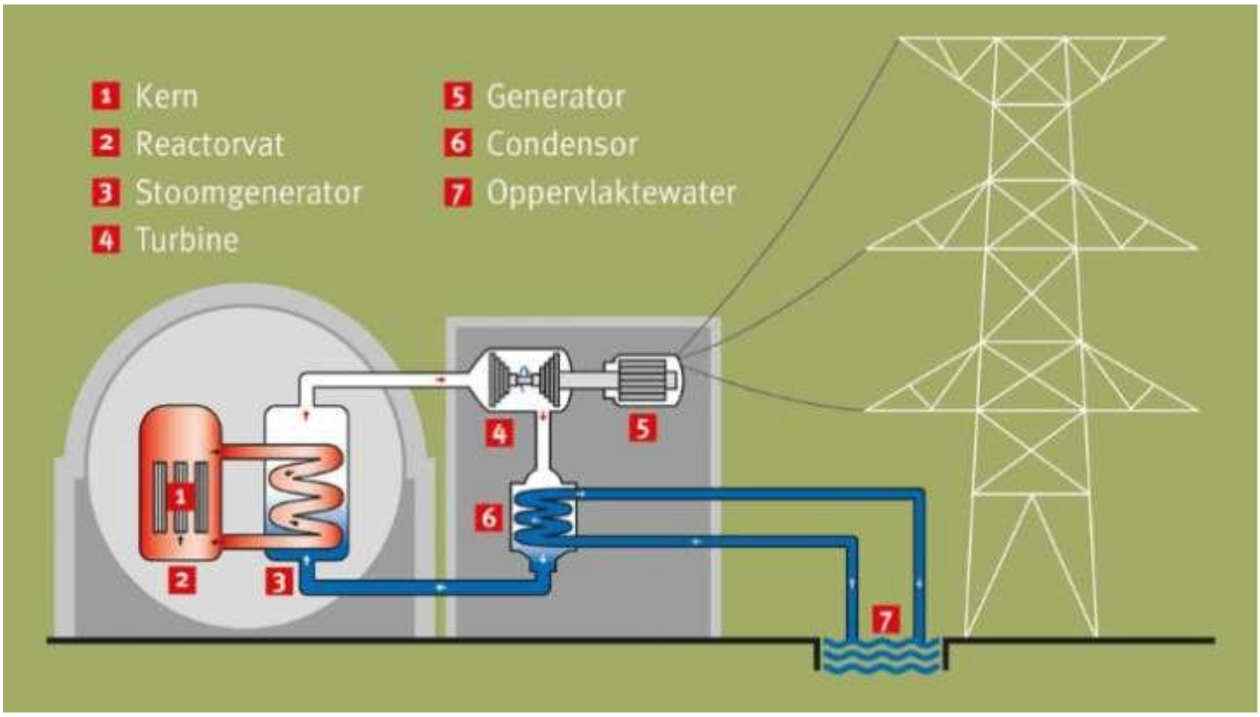
When people think of green electricity, they often think of wind turbines, but there are also other ways to generate electricity in a sustainable way. One can use the sun, water or the earth. Grey electricity is generated using **fossil fuels** such as oil, gas or coal. This is also called environmentally harmful or non-sustainable electricity. It is mainly the waste materials that are bad for the environment.

4.1 How does a nuclear plant work?

Nuclear energy is energy released by **fission atomic nuclei** of uranium. This energy can be used to make electric current. It is a relatively clean form of energy, which does not release any direct CO2. Belgium currently has 2 nuclear power plants: Doel and Tihange.

Doel Nuclear Power Plant *Reactor Vessel*

A nuclear power plant basically works like **a big steam engine**. The difference lies in the fuel: **uranium** instead of coal. In a nuclear power plant, uranium atoms are split in a reactor that produce heat. They use this to make steam that drives a turbine that generates electricity. Because radioactive substances are also produced in the process, a nuclear power plant has many **safety features**.



Schematic representation of a nuclear power plant

At the heart of the nuclear power plant is the core (1) with the nuclear fuel, safely shielded by steel and concrete. Heat is produced in the core by fission uranium cores in the nuclear fuel. Hence the name **nuclear fuel**.

The **heat** from nuclear fission is absorbed by water from the first (nuclear) cycle. This circulates under high pressure through the reactor vessel (2). This heat is used to make **steam** in the second (non-nuclear) circuit of the steam generator (3). The steam drives a turbine (4). It sits on a shaft that drives **a generator** (5).
The power generated by the generator is supplied to the **electricity grid** . The hot steam is placed in a condenser (6) Cooled to water. This cooling is done by feeding cold surface water (7) past the steam system.
Is nuclear energy **sustainable**? The European Parliament thinks so. At the beginning of July 2022, Brussels decided that European investments in gas and nuclear energy will be labelled green. A maximum of CO2 emissions per kWh must be taken into account. It is variable per country and is calculated on the composition of the production park.

No CO2 is emitted when generating electricity in a nuclear power plant. CO2 emissions do occur during the construction and dismantling of the power plants, during the extraction and transport of uranium and during the transport, processing and storage of nuclear waste. The international panel of climate scientists IPCC has calculated that over the entire life cycle, the total greenhouse gas emissions from nuclear energy are about 40 times lower compared to natural gas. This is comparable to the emissions associated with wind energy and even lower than those associated with solar energy.

Uranium used as nuclear fuel in nuclear energy is **a non-renewable raw material** and can therefore run out, just like natural gas and coal. That is why nuclear energy now falls under gray electricity. Tests are currently being carried out on other fissile substances such as **thorium**. However, a breakthrough in this material is not expected before 2050.

Generation creates waste that is difficult to store. But little CO2 is released. That is why scientists, the European Commission and the government are investigating whether we can use nuclear energy in the future. For the time being, it remains a sensitive subject with supporters and opponents.

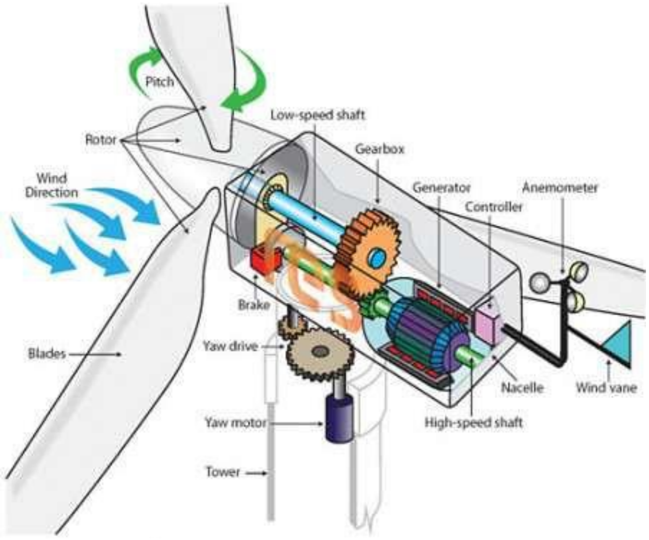
More information about the operation of a nuclear power plant? Follow the link and discover the process from nuclear fission to electric current!

4.2 How does a wind turbine work?

The principle of a windmill or **wind turbine** is simple: the wind makes the blades rotate, and this movement is converted into electricity.

Most modern wind turbines have **three rotor blades** or the blades. The point where the blades meet is called the **rotor** . The wind causes the whole thing to turn.

The rotor is linked to a **nacelle** or the housing at the top of the mast. A motor ensures that the nacelle is always positioned in such a way that the blades are oriented towards the wind. To determine the correct direction of the nacelle, a wind vane on top of the mill continuously measures the wind direction.



In the nacelle there is a **generator**: a large **dynamo** that converts the rotating motion of the rotor into electricity. This can be compared to a simple bicycle dynamo. This effect will be discussed further later.

Because the rotor has a relatively low speed, a gearbox will ensure a conversion to a higher speed. This is necessary so that the generator **can generate** enough electricity.

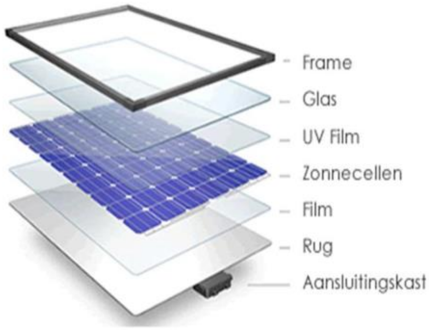
There are different versions of wind turbines: **vertical** and **horizontal**.

Vertical and horizontal wind turbines

4.3 What is a solar panel?

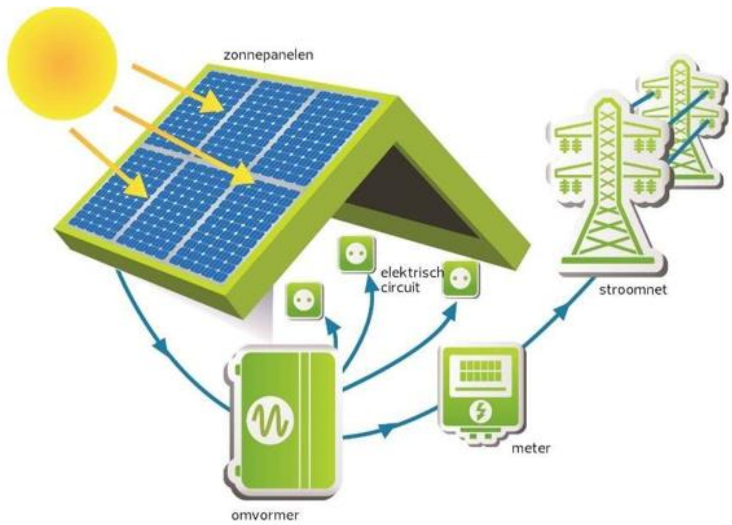
In 1839, the French physicist Becquerel discovered the so-called photovoltaic effect: that you can generate electricity from sunlight.

A solar panel consists of several cells that are usually made of **silicon** . The moment sunlight falls on the solar panel, the solar energy releases electrons in the silicon. This creates **a voltage difference** between the top and bottom of the cells.



Solar panel construction

The top is positively charged and the bottom negatively, creating direct current. By connecting several solar panels to each other, an electrical circuit is created and current can flow through the panels.
An **inverter** plays an essential role in any solar panel installation. The **direct current** generated by solar panels must be converted into **alternating current** that can be used in a home. After the inverter has converted the power and shared it with the meter box, one can use the alternating current from solar panels via **sockets.**



Schematic representation of the use of solar panels

How a solar panel works

The operation of **an inverter** consists of a few simple steps:

- The DC current generated goes to the inverter via a cable.
- In the inverter, the direct current (DC) is converted into alternating current (AC).
- The alternating current goes to the meter cupboard so that it can be distributed in the house. Excess generated energy is transferred to the electricity grid where it will be settled.

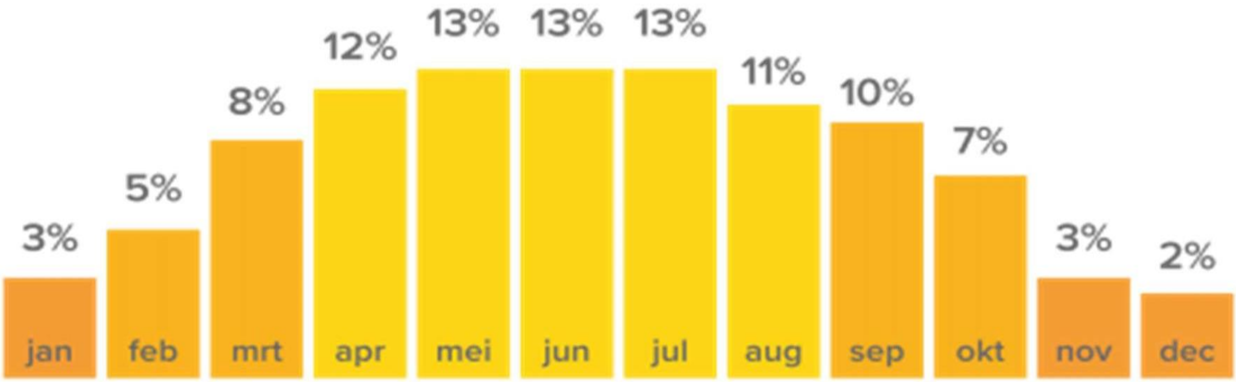
It is also possible to store in **a home battery** and home battery = direct current! This is usually used to charge an electric car.

The sun does not have to shine brightly to generate power with solar panels. Solar panels also produce electricity on cloudy days. **However, shade** does have an effect on the effect. When shadow falls on a solar cell, less current can flow through the cell.

The power of solar panels is expressed in watts. However, the production of electricity is not always the same, because the amount of sunlight on the solar panels is constantly changing. Temperature, the placement of the solar panels and the types of solar panels also affect the yield. For this reason, the **maximum power is** indicated for solar panels, expressed in watt peak (= Wp).

This maximum power is determined in a test environment with ideal conditions. When calculating the actual yield, installers use special software to combine the weather conditions with the angle of inclination of a roof and the wind direction of the panel. This makes it possible to calculate how many panels are needed to provide a home with sufficient power.

The yield of solar panels differs per month because it **depends on** the radiation intensity of the sun.



Percentage distribution of the annual yield of solar panels.

5. HYDROGEN: the future?

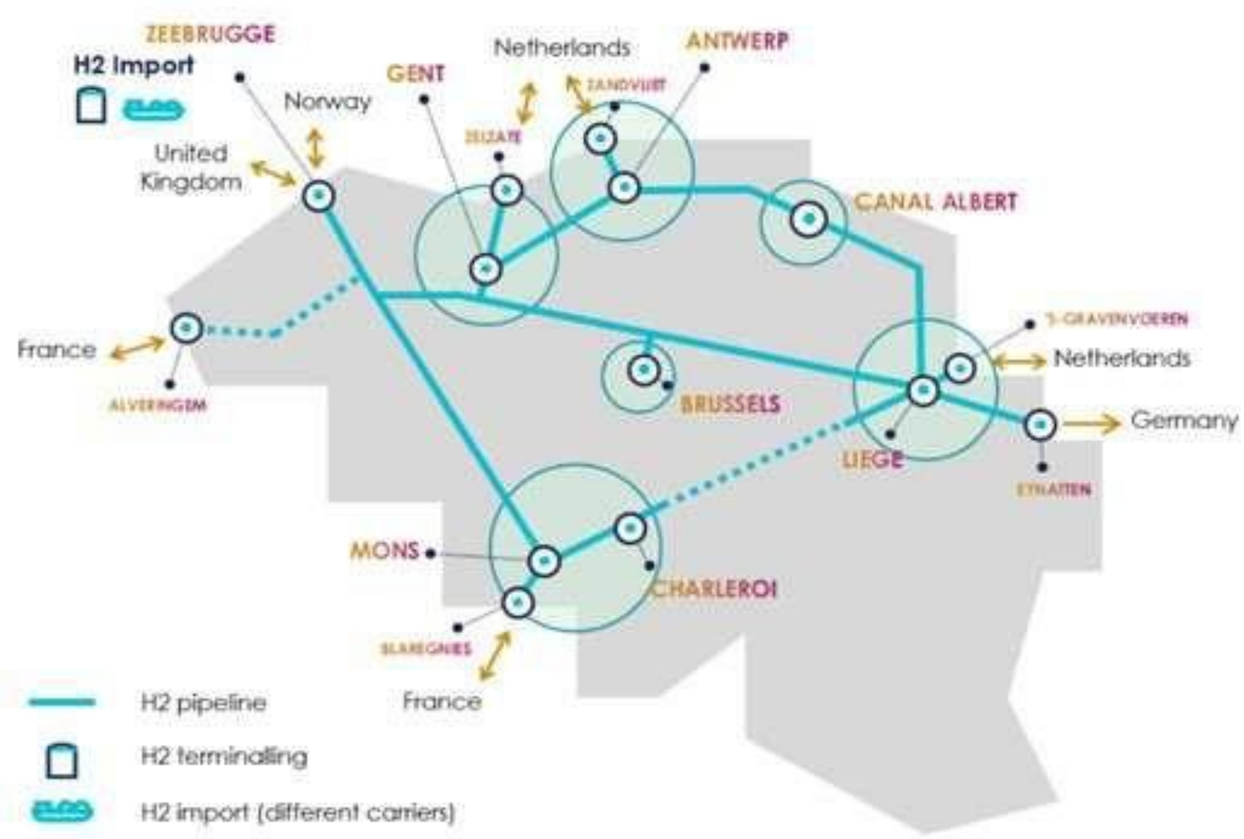
The aforementioned procedures for generating electrical energy have now become established in Belgium and people continue to look for **sustainable energy supply**. In recent years, more has been invested in research into a new technology: hydrogen (H2)!

Did you know that Belgium is a global player in the treatment of hydrogen? Our petrochemical and chemical industry processes 6 billion m³ of hydrogen annually. The industry around the port of Antwerp in particular is a major customer.
In addition, we also have one of the largest hydrogen networks in the world: more than 600 kilometres of underground pipelines cross our country.

Hydrogen has been an important element in the chemical and petrochemical industry since before the Second World War. It is made by cracking natural gas and also exchanged between the various industrial clusters in our country and our neighbouring countries France and the Netherlands.

There are no fewer than 613 kilometres of hydrogen pipelines in Belgium, with nodes around the ports of Ghent and Antwerp. No other country in the world has such an extensive network.

In Germany there are 375 kilometres, in the Netherlands about 360 and in France about 300. Great Britain has barely 40 kilometres of pipelines. There are 1,200 kilometres in the whole of the US, especially in Texas and Louisiana. But the US is more than 300 times larger than Belgium!



Overview of the hydrogen pipelines in Belgium.

The Belgian network is the merit of one company, Air Liquide, which developed an extensive system of pipelines for industrial gases in the 1960s. In 1938, the first pipelines were laid in our country.

Industrially produced hydrogen flows through the current pipelines, split off during the processing of natural gas, or the residual fraction from, for example, chlorine plants. It is the most efficient way to make hydrogen. But natural gas is a greenhouse gas that is not a good thing for global warming. This is actually about grey hydrogen, not green hydrogen. It is mainly used for the processing of chemical or petrochemical products, for example to extract the polluting sulphur from petroleum.

Air Liquide is willing to equip the pipeline with hydrogen refuelling stations for electric cars and hydrogen-powered trucks. In the meantime, the first filling stations have already been connected to the pipeline.

Hydrogen filling stations are slowly starting to appear on the streets.

It is precisely this lack of filling stations that is playing a major role in the breakthrough of hydrogen cars. So these are electric cars that do not get their power from batteries, but from hydrogen. In five minutes, such a car is fully fuelled.

Hydrogen cars have been around for more than ten years. But as long as there are not enough filling stations, most manufacturers are postponing the large-scale launch of their hydrogen cars. Battery electric vehicles (BEV) are simpler in construction, cheaper to purchase, consume and maintain. The energy companies are postponing the launch of their filling stations as long as there are not enough hydrogen cars. A vicious circle, as a result of which the mass production of hydrogen cars is stagnating and the few available models are still extremely expensive. But thanks to the hydrogen pipelines, Belgium may have an extra trump card to break that deadlock.

The network could become the backbone of a whole series of petrol stations on Belgian soil. For the time being, not a single hydrogen filling station has been connected to the pipeline in Belgium. For the time being, the supply will be done with tankers.

It is not yet clear whether green hydrogen can also be injected into Air Liquide's network. But the pipelines could in any case already be an addition to truly green filling stations that get their hydrogen from solar or wind farms. Just as electric cars run on grey or green electricity, hydrogen cars could run on grey or green hydrogen.

The network is one of the many assets that our country has to build a hydrogen economy. But there are others: our companies. These can become the building blocks of a hydrogen economy.

The interest group WaterstofNet vzw has already developed several projects with companies. Among other things, for our transport.

This organisation approached Colruyt Group for this and they were interested in it. For example, since 2012, the distribution centre in Halle has been driving around with hydrogen – electric forklifts that get their hydrogen from Colruyt Group's solar panels and wind turbines.

The interest of the shipping industry has also been aroused. The Belgian shipping company CMB. TECH already has workboats and a smaller passenger boat powered by hydrogen: the Hydrocat 48. This vessel takes care of the transport of its maintenance personnel to one of the wind farms.

Meanwhile, the first ferries are running on hydrogen in Norway. The next step: larger sea-going vessels for the transport of containers as a clean alternative to the polluting fuel of the current ships. People are mainly looking at hydrogen derivatives such as ammonia and methanol.

Because hydrogen can provide both electricity and heat, there is also more and more interest from the energy sector. In 2013, for example, Umicore opened the largest hydrogen power plant in the world. It consisted of a container full of fuel cells on the site of Solvay's former chlorine plant. The plant supplied electricity and heat to Solvay's plant. It was fed with the surplus hydrogen that came from the same factory. The plant has been running for about 10,000 hours.

This project was stopped but was continued in the Chinese region of Xinjiang with a power plant twice as large. The individual tanks can store 21,000 m³ of hydrogen.

Due to competition from the Chinese market, Belgian companies cannot be left behind. The Antwerp-based company Umicore is interested in hydrogen technology because it can supply the necessary precious metals for the fuel cells that extract the electricity and heat from the hydrogen. These fuel cells can be used in power plants as well as in electric vehicles.

A second Flemish company plays a key role in this story: the SME Borit from Geel, where it makes the wafer-thin metal plates that make up fuel cells.

Agfa-Gevaert is also active in hydrogen technology: it manufactures the membranes of the electrolysis devices that split hydrogen from water.

But there are also other developments that focus on hydrogen-powered combustion engines. Classic engines, in other words, that power vehicles or larger power groups and now run mainly on diesel and petrol. But you can also run them on clean hydrogen. Larger motors can even provide companies and SMEs with power and heat.

Our country clearly has a number of unique assets to become a major player in a possible hydrogen economy. But there is a hurry: other countries are also seeing an increase in interest in hydrogen and are playing their economic trump cards. For example, Germany now has more than 100 public hydrogen filling stations. One must be added every two weeks. The small number of public petrol stations in Belgium contrasts sharply with this, especially when you know that we have almost twice as many pipelines as Germany. A coordinated policy therefore seems to be increasingly becoming a necessity in order not to miss the hydrogen train.

5.1 What is hydrogen?

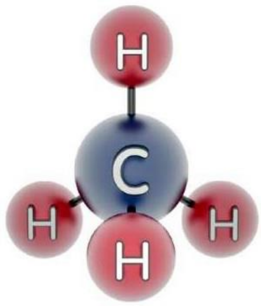
According to Mendeleev's periodic table, hydrogen with symbol is capital H, the first element and most abundant element in our universe.

A hydrogen atom consists of only one proton with a positive charge and one electron with a negative charge. It is the smallest molecule that exists with a diameter of 2.9 x 10-10m. For comparison: diameter methane molecule CH4 (natural gas) = 3.8 x 10-10m.

Under normal circumstances, it does not occur as a single element but in a compound.

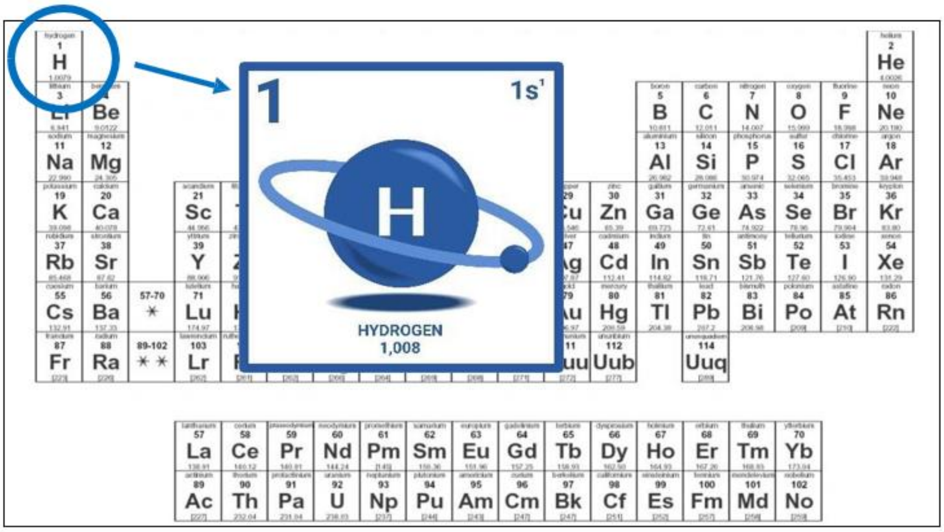
This will be referred to as dihydrogen with the formula H2.

Under normal conditions, hydrogen (H2) is a colourless, flammable and transparent gas. It belongs to the group of non-metals and is the lightest gas known. Per weight in (in kg), hydrogen does have a high energy density of 120 megajoules (MJ) per kg. That is almost three times as much as natural gas (45 MJ per kg).



Molecule methane CH4

In 1671, the Irish-English chemist Robert Boyle described that a gas was flammable. This was released during a reaction between iron and a dilute acid. The English physicist Henry Cavendish (1731 – 1810) discovered during an experiment with mercury in 1766 that this gas was a chemical element. He was able to accurately describe many properties of the gas but suspected that the metal was the source rather than the acid. He therefore called his newly discovered element flammable gas of metals. A few years later, Antoine Lavoisier gave the element the current name of hydrogen: **Hydrogenium.**

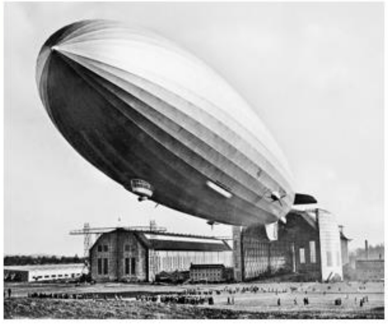


Hydrogen on Mendeleev's table and was discovered by Henry Cavendish in 1766

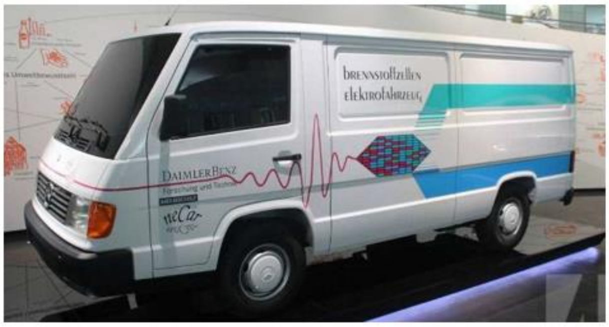
This element has come a long way in the meantime. Some historical dates...

1800	The first application of **electrolysis**.
1838	Development of the first **fuel cell**.
1874	Jules Verne already predicted the use of hydrogen as a fuel **in the future**.
1920	The first hydrogen-powered engines.
1937	Zeppelin The Hindenburg on **hydrogen**: disaster is caused by the flammable paint on the frame!
1958	NASA develops **liquid hydrogen** fuel cells.
1994	The first hydrogen-powered **car** will travel over a distance of 130 km at an average speed of 90 km/h.
1999	In Europe, 30 **buses** run on hydrogen.

1874: Jules Verne



1937: Hindenburg



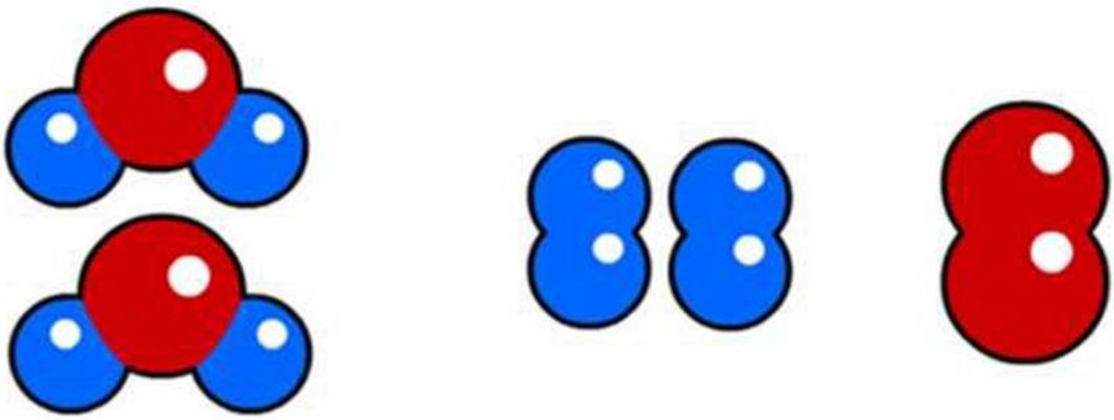
1994: Daimler Benz Necar

The chemical element hydrogen makes up 75 percent of the total mass of the universe. For example, the sun consists of more than two-thirds of hydrogen. In addition, it is also found in water, all living organisms and fossil fuels on earth.

Hydrogen is in its purest form colour – and odourless and non-toxic at room temperature. At temperatures lower than -252.77 °C, hydrogen becomes liquid. If it is cooled even further to below -259.2 °C, it will take on a solid form.

Hydrogen does not exist on earth on its own. The atom is usually a part of larger molecules, connected to other atoms such as acid or carbon. As a result, it has to be soaked out of components that contain it, such as water (H2O).

For this, the **reaction equation below is used**.



$$2H_2O \rightarrow 2H_2 + O_2$$

Energy is released during the conversion of hydrogen and oxygen into water. This **energy** was used to make hydrogen. So hydrogen can be made from water with sustainably generated electricity, which is called **green hydrogen**.

Read the different cases and make the correct calculation.

One can get 55 grams of hydrogen from a 0.5 liter bottle of water. A hydrogen-powered car consumes about 1000 grams per 100 kilometers. How many kilometers can one drive with water from 1 bottle?

Work with 'Given'/'Asked'/'Solution'

A hydrogen-powered car wants to drive 125 kilometers. How many 0.75 liter bottles of water do you need? Some data is taken from the previous issue!

Hydrogen (H) is also an important component of all organic matter, such as coal, petroleum or gas, and biomass gases. Hydrogen can also be produced from these materials, but the sustainability of such processes is largely determined by the molecular parts that "remain" after the hydrogen (H) atoms have been loosened.

In the case of water, oxygen (O2) remains as a residual product. In organic matter, the remaining carbon atoms form new molecules with oxygen atoms from the environment and the process results in carbon dioxide (CO2). If this is released into our atmosphere, it will intensify climate change.

Separating hydrogen atoms from larger molecules is energy-consuming, which is also the power of hydrogen. When pure hydrogen is released again to form bonds with other atoms and return to a state that occurs in nature, that large amount of energy from the detachment is released again.

Hydrogen is therefore suitable as **an energy carrier** for storing and transporting energy as a liquid, compressed gas or in solid form.

The production of hydrogen or the detachment of the H atoms from larger molecules therefore requires an energy source. In the case of water, (green) electricity can be used to pull apart the hydrogen and oxygen atoms.

In hydrogen made from fossil fuels, the (heat) energy from the fossil fuel is often used to form hydrogen from the fossil atoms and water that is often added in the form of steam at high temperatures.

The nature of that source will **determine the durability** of the hydrogen, which will be referred to as **colors** such as gray, blue and green. In the near future, people will also talk about gold with the sun as its source.

In summary, we can say that hydrogen is the simplest chemical element. It normally has the following characteristics:

COLORLESS	NON-CORROSIVE	NON-OXIDIZING
NON-RADIOACTIVE	Non-carcinogenic	NON-TOXIC

5.2 The properties of hydrogen?

Some of the most important properties of hydrogen have already been mentioned in the previous point. Below we briefly discuss these again and supplement them with the other properties:

- Hydrogen is the smallest molecule.
- Low density.
- Odourless, colourless and non-toxic.
- Combustion gives water.
- Low ignition energy.
- Wide flammability range.
- A hydrogen flame radiates little heat because the heat remains in the flame.
- Hydrogen burns at a high speed.

Hydrogen is a gas and has a low density.

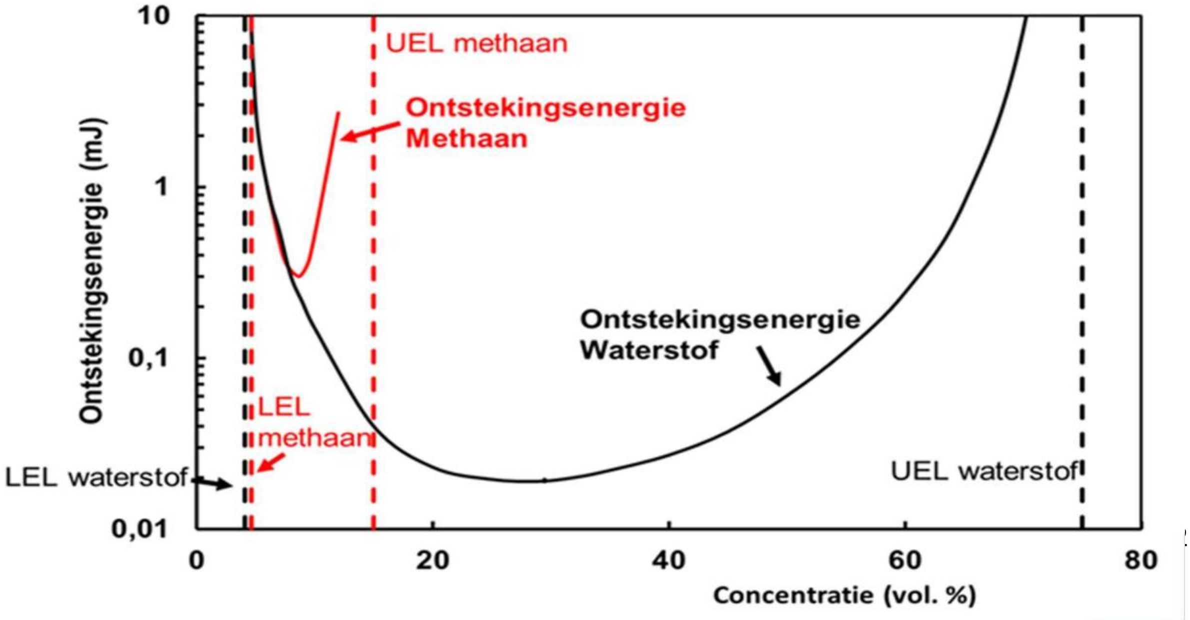
- Under normal circumstances, hydrogen is a gas.
- It has a low density: 1 Liter weighs 0.083 grams.
- 1 Liter of air weighs about 1.2 grams, making hydrogen 14 times lighter than air.
- Hydrogen rises the fastest of all substances.

The combustion of hydrogen gives water.

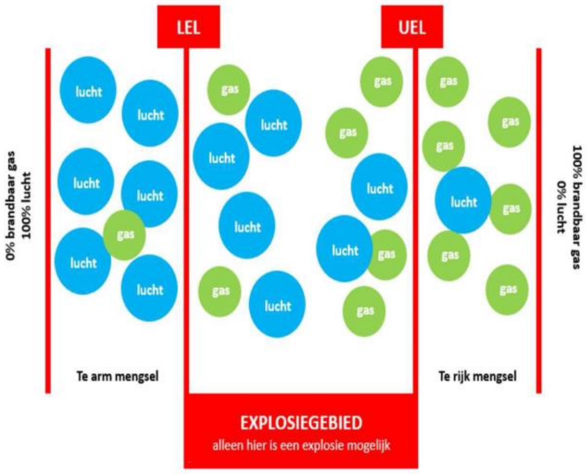
- Water **is produced when hydrogen is** burned: 2H2 + O_2 = 2H2O
- Hydrogen does not contain carbon, so **no CO2** is released during combustion.

Hydrogen has a low ignition energy.

- The **ignition energy** of hydrogen depends on the **concentration of** hydrogen, which will be expressed in vol.%.
- The lowest ignition energy of hydrogen is at 30 vol.% and has an ignition energy of **0.019 mJ**.
- With natural gas, the lowest ignition energy is higher: 0.3 mJ.



Hydrogen has a wide flammability range.



If you are going to mix 2 substances, you also speak of **the explosion area**.

The ratio between the 2 substances must be within the explosion limits.

- **Lower explosion limit**
  (LEL – Lower Explosion Limit):
  minimum amount of gas or vapor in the air to cause an explosion. To work safely, you must always stay well below the LEL!
- **Upper explosion limit**
  (UEL – Upper Explosion Limit):
  maximum amount of gas or vapor in the air to cause an explosion.

If a mixture contains too little explosive substance, it is called **a lean mixture** that cannot explode. Too much explosive substance is **a rich mixture** and cannot explode.

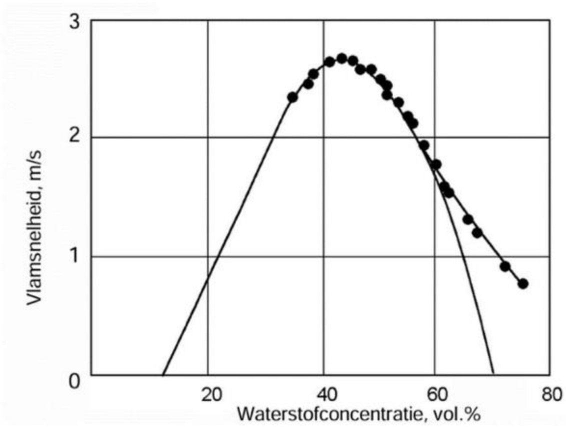
The lower explosion limit (LEL) of hydrogen is 4% by volume while the upper explosion limit is 75% by volume. This is **much wider** than the flammability limit for natural gas.

The heat and speed of a hydrogen flame?

Hydrogen does not contain **carbon** , so no soot particles will be formed during combustion.

Due to the absence of these particles, a hydrogen flame **colorless** and the flame also radiates **little heat** .

The **flame speed** depends on the hydrogen concentration and it can reach more than 2 meters per second.



Flame speed of hydrogen is more than 2 m/s.

Hydrogen has a high energy density per kilogram.

Hydrogen contains **a lot of energy per kg** and is much more compared to other fuels. It is more than 3 times as much compared to natural gas. As a unit, one speaks of kilowatt hours per kilogram or kWh/kg. Energy density has an upper and a lower limit: low heating value or high heating value.

When incinerating or converting to energy, the question is whether all the heat that is released in the process is also captured and used. If that is the case, it is called a high heating value or the upper limit.

FUEL	ENERGY DENSITY
Hydrogen	33,3 – 39,4 kWh/kg
Natural gas	11,7 – 15,3 kWh/kg
	12,8 – 14,2 kWh/kg
	12,2 – 12,8 kWh/kg

FUEL	ENERGY DENSITY
	11,7 – 12,8 kWh/kg
Crude oil	11,7 – 13,1 kWh/kg
	6,6 kWh/kg
	6,3 kWh/kg

Overview of fuels and energy density.

Purity of hydrogen

When making hydrogen, impurities come with it. Depending on the production method and the raw material from which the hydrogen is made. These impurities can include water, oxygen, carbon monoxide, nitrogen, carbon dioxide, and other substances. For example, a fuel cell needs a hydrogen purity of 99.999% hydrogen and requirements have been set for the 0.0001% impurity. Hydrogen as a raw material or used in combustion has a different standard each time.

HYDROGEN	PURITY	IMPURITIES
Hydrogen 3.0	≥ 99,9%	H_2O < 30 ppm
Hydrogen 4.0	≥ 99,99%	H_2O ≤ 20 ppmO_2 ≤ 10 ppm
Hydrogen 5.0	≥ 99,999%	H_2O ≤ 5 ppmN_2 ≤ 3 ppmO_2 ≤ 2 ppmC_xH_y ≤ 0.5 ppm
Hydrogen 6.0	≥ 99,9999%	H_2O ≤ 0.5 ppmN_2 ≤ 0.5 ppmO_2 ≤ 0.5 ppmC_xH_y ≤ 0.1 ppmCO ≤ 0.1 ppmCO_2 ≤ 0.1 ppm

Overview of purities and impurities of hydrogen, source Linde gas industrial gas data sheets.

What is the capacity for a 600 L gas cylinder in m³?	
What is the purity of Hydrogen 5.0?	
Wat is de aansluiting van de gasfles?	
Which wire connection is used?	
What direction does the thread on the bottle have?	
What is the colour of the shoulder and cylindrical part of the gas bottle?	
What standard does the connection have?	

Hydrogen 5.0

For which applications is this gas used?

____

____

____

____

Hydrogen is an excellent energy carrier.

Hydrogen is seen as an important energy carrier for storing surplus green energy **for a long time**, for example.

Hydrogen, on the other hand, loses hardly any energy over longer periods and will be used to store energy. In this way, the effect of summer and winter can be bridged in the future. Experiments are underway with **salt caverns** and **gas fields**.

The possibility of storing hydrogen in salt caverns has already been proven in projects in England and the United States. In the Netherlands, there is a pilot project at the salt caverns in Zuidwending.

Just like under land, there are several salt structures under the North Sea that may be suitable. Exploration studies, including exploratory drillings, are needed to confirm the possibilities at individual locations.

Principle salt caverns in Zuidwending.

There are many gas fields in the North Sea that may be eligible for hydrogen storage. Most of these gas fields have already been developed and connected to a platform and natural gas infrastructure. However, the technical feasibility of hydrogen storage in gas fields has yet to be definitively proven.

Underground hydrogen storage can serve a variety of purposes, similar to natural gas storage: short-cycle storage, seasonal storage, and strategic storage. Depending on the type of storage, the costs of the necessary facilities and infrastructure at sea are between one and a half and two and a half times higher than on land.

For seasonal storage and strategic storage, the amount of gas required to keep the repository pressurized – the so-called cushion gas – has a share of about 60-70% in the costs. This part of the costs does not differ from underground hydrogen storage on land.

Compare the properties below and place one of the following fuels in the right place: petrol, diesel, CNG, LPG and hydrogen.

LPG = Liquefied Petroleum Gas
. CNG = Compressed Natural

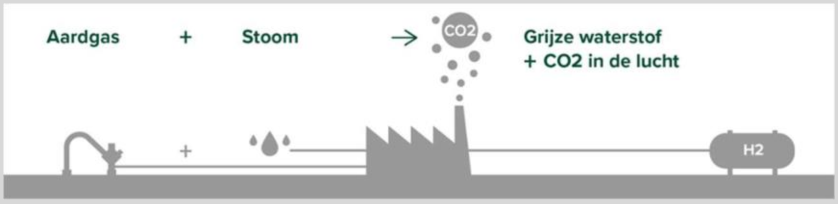
Composition	$C_8 - C_{25}$	$C_4 - C_{12}$	C_3H_8 & C_4H_{10}	CH_4	H_2
Average density	840g/l liquid	750g/l liquid	2,25g/l gas	0,83g/l gas	0,09g/l gas
Ignition temperature	220°C	220 – 280°C	460°C	595°C	585°C
Accumulation point in case of leakage	Soil	Soil	Soil	Dissemination	Dissemination
Range with 10 litres of fuel	185km	167km	119km	40km at 200bar or 20MPa	25km at 700 bar or 70MPa

6. PRODUCTION OF HYDROGEN

Currently, most hydrogen is made from methane, which will release greenhouse gases. This is called grey hydrogen. The sustainability of hydrogen depends on **the production method** and will be shown in **colours**.

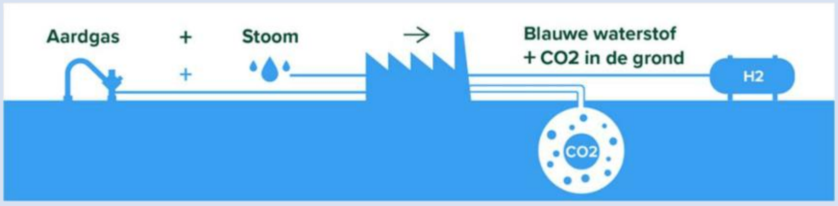
Grey hydrogen: hydrogen production based on fossil fuels, such as coal, natural gas and petroleum, releasing about 9 tonnes of CO2 into the air per tonne of hydrogen.

Currently, about 95% of the hydrogen produced in the world is made in this way, often on the basis of natural gas via large reformers. People often talk about SMR = steam methane reforming.

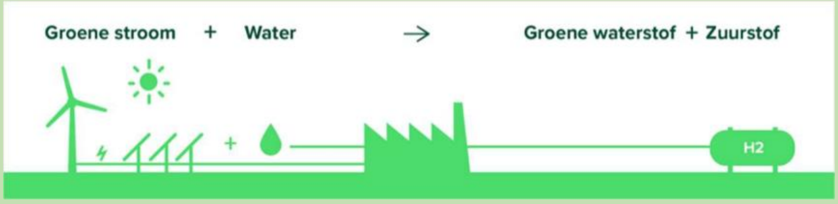


Blue hydrogen: in the production process of grey hydrogen, the CO2 is (largely) captured and stored. This is referred to as CCS = carbon capture and storage.

It can also be used as a raw material under the name CCU = carbon capture and utilisation. The production of chlorine also produces residual hydrogen.



Hydrogen becomes green when it is made via electrolysis where water is split into hydrogen and oxygen by means of renewable electricity.



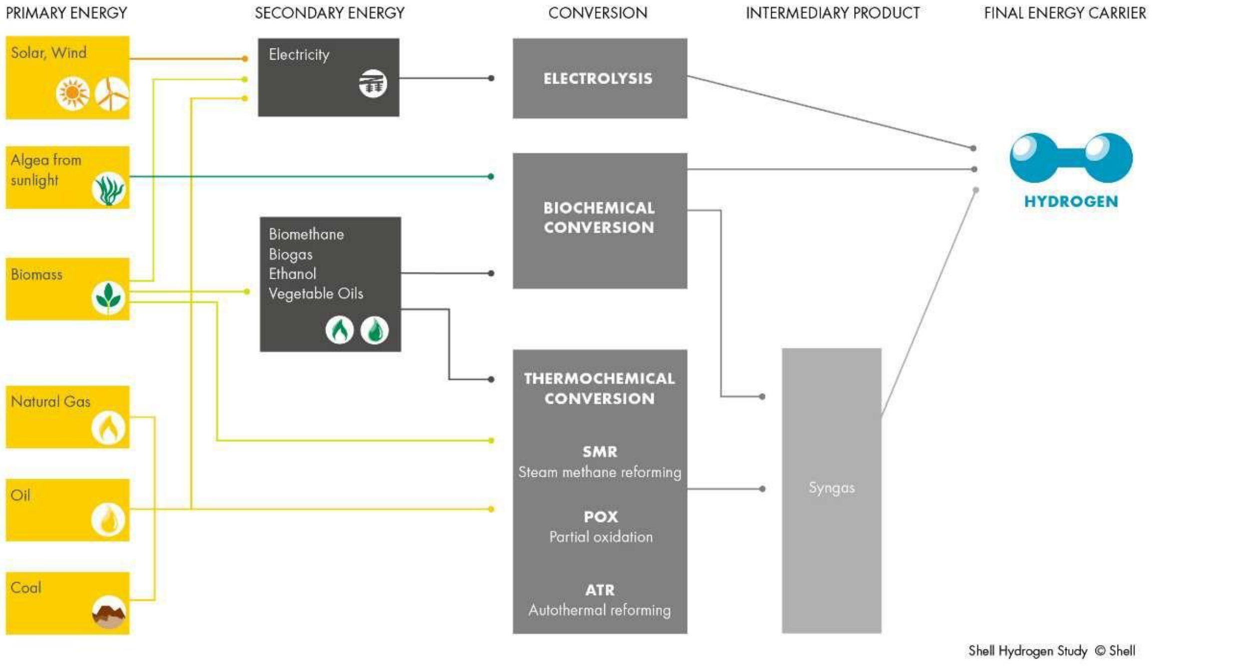
Pink hydrogen is hydrogen produced from water and electricity from nuclear power plants. This does not release any CO2 emissions, but links the specific characteristics of nuclear energy, including waste, to the hydrogen produced.

When hydrogen occurs in nature in its purest form, it is called white hydrogen. This hydrogen can "just" be extracted from the ground, just as is the case with natural gas. However, we have learned that no CO2 is released when hydrogen is used, whereas natural gas does. In addition, you don't need electricity or petroleum to produce this hydrogen, because white hydrogen is already pure.

White hydrogen is therefore the best form of hydrogen, but it is unclear how much white hydrogen is available on Earth. We now know that white hydrogen can be found deep in the earth's soil thanks to chemical reactions, mainly in Africa. Since 2011, for example, white hydrogen has been generated in villages in Mali and used as an energy source. But now there is also belief that there is white hydrogen in the ground in many more places in the world and extensive research is being done. Among others in South America, Australia and the United States, but also in European countries such as France and Spain.

Nowadays, people are looking for other renewable sources of hydrogen. At KU Leuven, the development of a hydrogen panel is in full swing. Will people be talking about the golden hydrogen in a few years' time?

The production of hydrogen becomes clearer if one looks at an overview of **the energy chains** as shown in the figure below.



We discover the following **primary energy sources** that are renewable: solar, wind, algae production on sunlight and biomass. The fossil and non-renewable energy sources are natural gas, oil and coal.

The **secondary energy source** is referred to as an energy carrier before hydrogen can be produced. An example of this is the generation of electricity.

There are 3 options for conversion or conversion:

- **Electrolysis**: production of hydrogen and oxygen from water.
- **Biochemical conversion** in which hydrogen is produced from algae.
- **Thermographic conversion** from fuels in the chemical industry.

In addition, there may also be **intermediate products** such as syngas. This is a gas mixture of hydrogen and carbon monoxide.
At the end of the chain, the product will be hydrogen, the **purity** of which will determine the application. For fuel cells, it is necessary to **use pure hydrogen**.

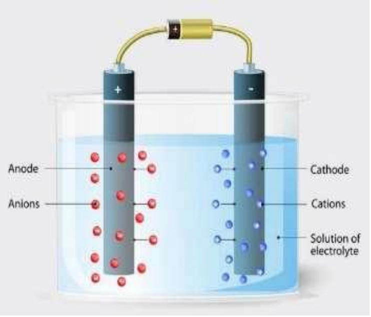
This diversity of potential sources of supply is the main reason why hydrogen is such a promising energy carrier.

6.1 Elektrolysis

Electrolysis is the process in which electricity reacts with water to separate hydrogen and oxygen. The end product is **pure hydrogen gas**. A modern electrolysis plant aims for an efficiency of approximately 80%.

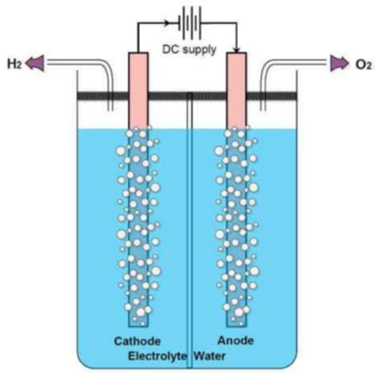
An electrolysis system consists of several parts. In theory, it is a vessel of water containing one electrolyte and two electrodes with a cathode and anode.

Electrolytes are chemical compounds that are partially or completely split into ions in a solution or in a molten state, allowing the solution or liquid to conduct an electric current.



The **cathode** is the negative pole and the **anode** is the positive pole. When electricity is conducted to both electrodes, a reaction will take place on both sides of the electrolyte.

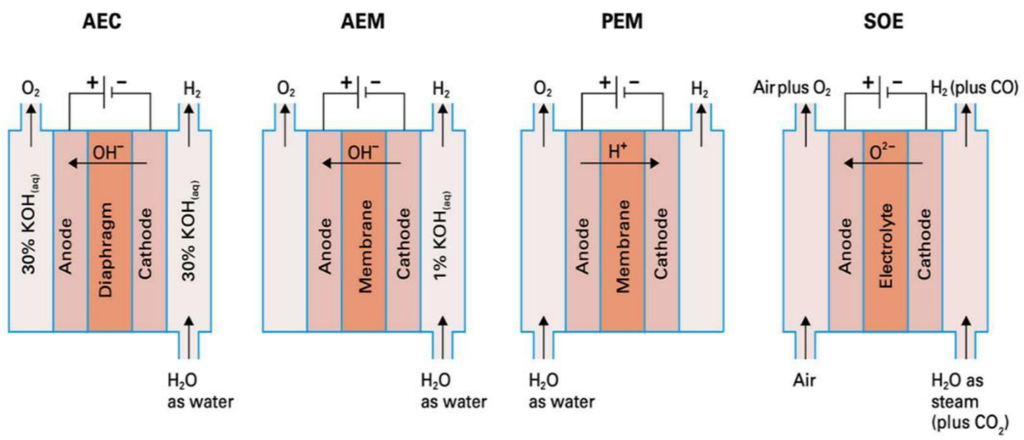
For example, hydrogen gas is released at the cathode and oxygen at the anode. The ratio of hydrogen to oxygen consists of 1/9. The oxygen is released or collected and the hydrogen gas is converted into **a liquid form**.



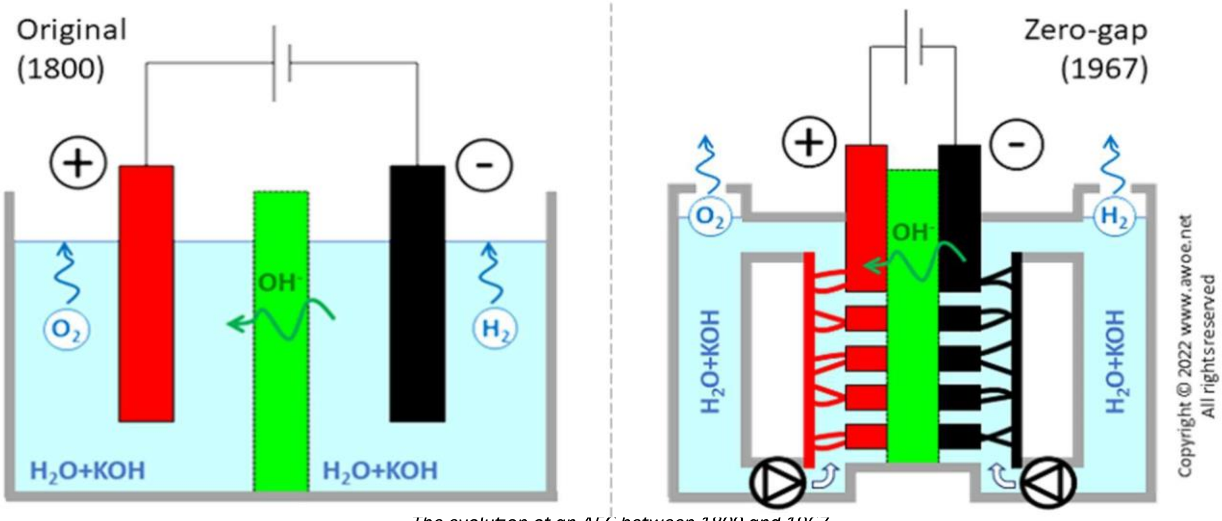
A **membrane** prevents product gases H2 and O2 from mixing, but allows the OH ions to pass through. The electrolysers consist of individual cells and central system units. By combining electrolytic cells in **a stack**, the hydrogen production can be adapted to individual needs.

In this way, there are different forms of electrolysers:

Alkaline Electrolysis Cell	**AEC of AEL**
Anion Exchange Membrane or Alkaline Electrolyte Membrane	**AEM**
Polymer Electrolyte Membrane or Proton Exchange Membrane	**PEM of PEMEL**
Solid Oxide Electrolysis Cell	**SOE of SOEC**



The most common are **AEC** and **PEM**. Both have slightly different **specifications** and therefore have their own advantages and disadvantages.

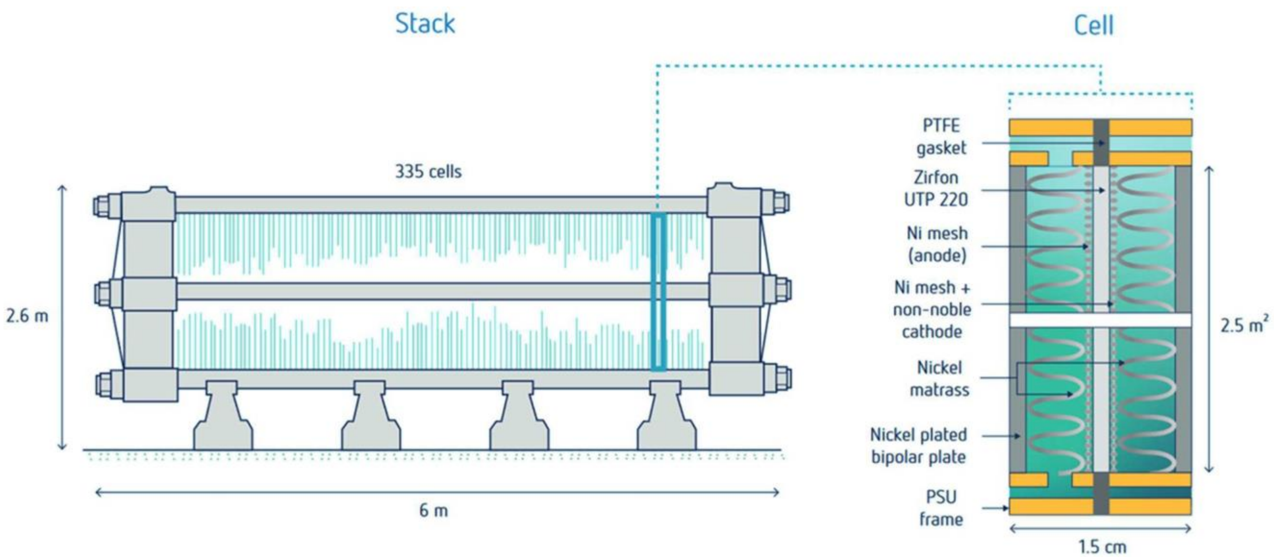


The evolution of an AEC between 1800 and 1967.

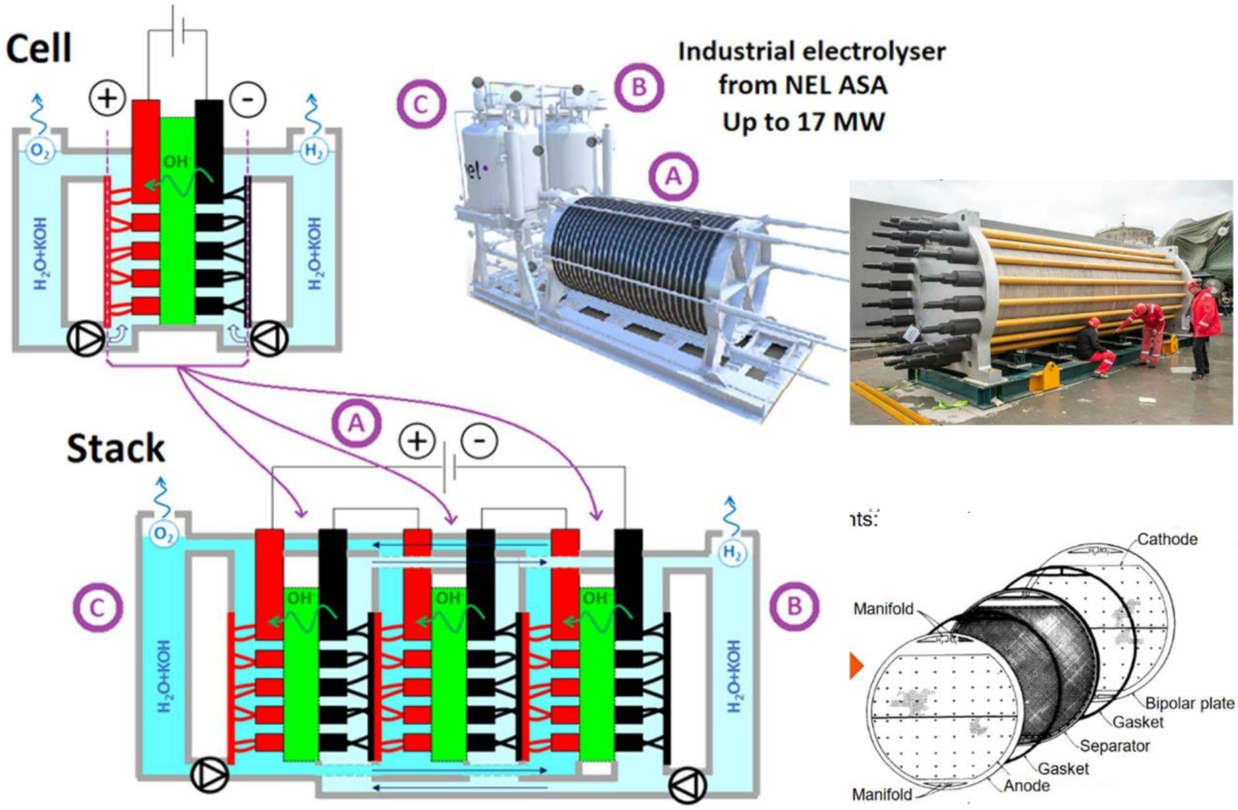
The **alkaline electrolyser** (AEC or AEL) uses a liquid alkaline electrolyte to split water into hydrogen and hydroxide ions at the cathode. These ions react at the anode to form water and oxygen. The total reaction is: H2O → H2 + 1/2 O2. This reaction requires approximately 285 kJ/mol of renewable energy, consisting of heat and electricity. Electrolysis takes place at temperatures between 40 and 90 °C.

Although electrolysers with a liquid alkaline solution of sodium or potassium hydroxide as an electrolyte have been available for a long time and have been successful in the production of hydrogen, there are some **drawbacks**:

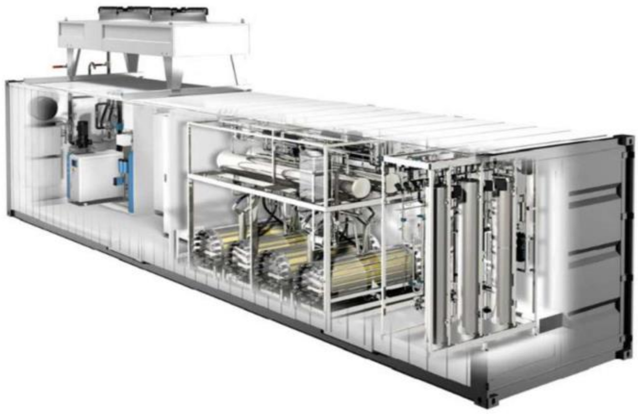
- low current density of the cells.
- the limitation that they cannot work under high pressure, making them relatively large in size.
  This is made clear by the image below.

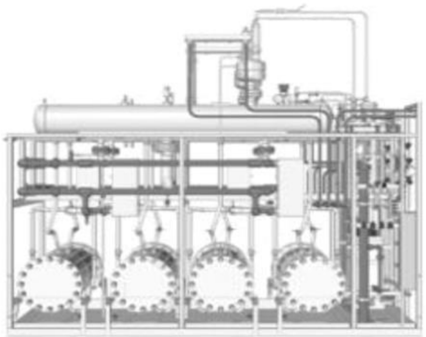


A stack consists of several cells.

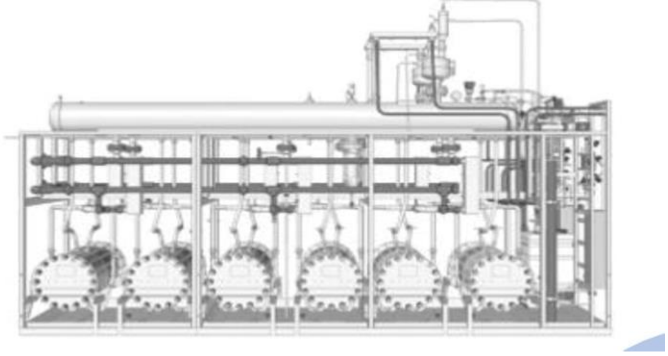


Schematic representation of an industrial AEC stack.





4 cell stacks = 70 Nm³/h



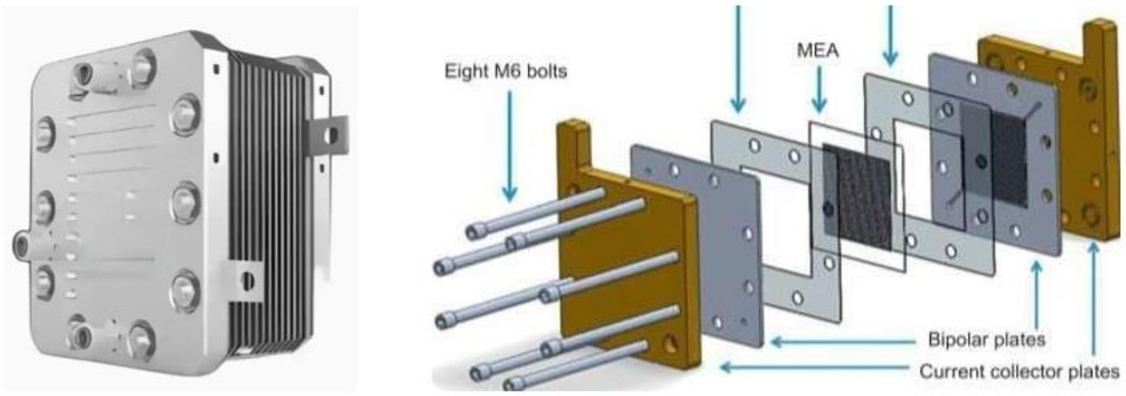
6 cell stacks = 100 Nm³/h

A **PEM electrolyser** (sometimes also called PEMEL) uses a polymer membrane (MEA = Membrane Electrode Assembly) that only allows hydrogen ions to pass through. The membrane ensures that water is split into oxygen, hydrogen ions and electrons at the anode, after which the hydrogen ions and electrons reach the cathode and are converted into hydrogen.

Chemical reactions take place at both the anode and the cathode:

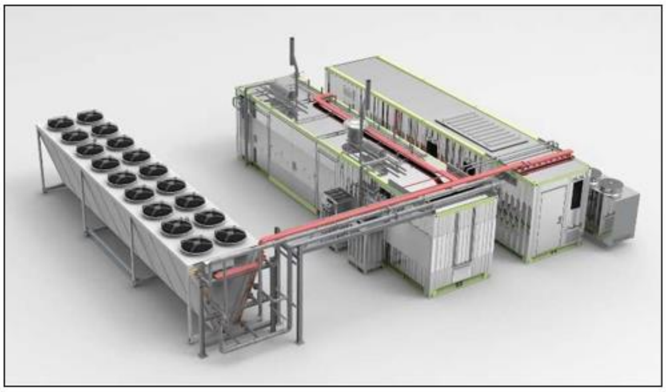
- Anode: H2O → H2 + ½ O2 + 2e
- Cathode: 2H+ + 2e → H2

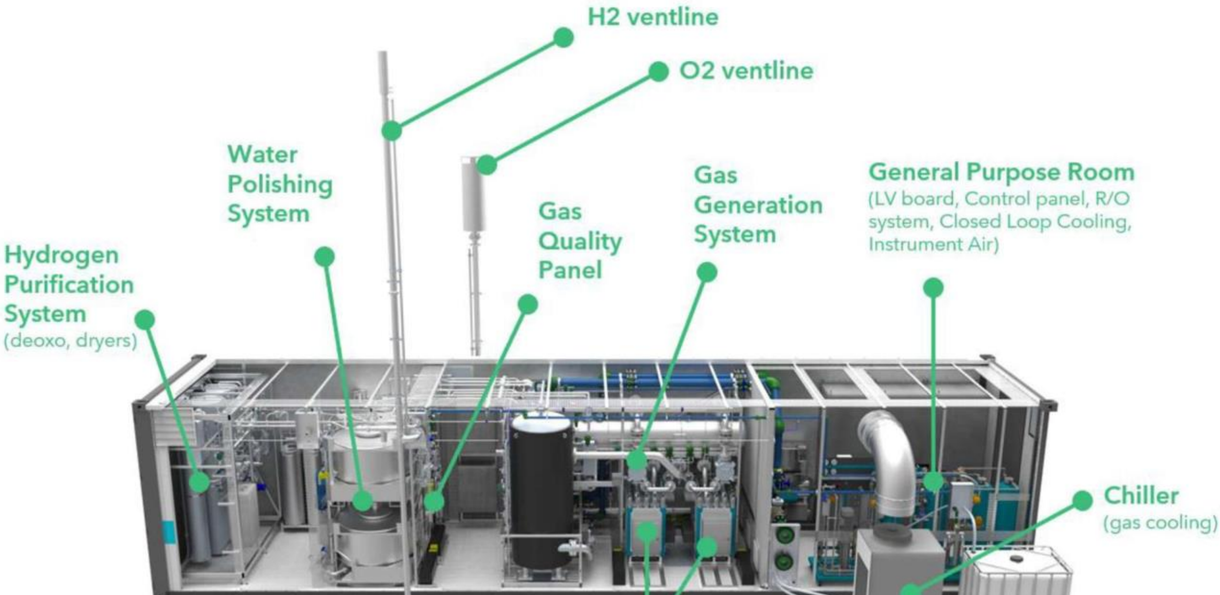
The PEM electrolyser has the advantage over the alkaline electrolyser that it can work under pressure and can therefore be more compact. However, there are also disadvantages, such as the need to work in very acidic conditions, which places special demands on the system.



Schematic representation of a PEM electrolyser.

An industrial installation in which PEM uses electrolysers consists of various components such as a process container, power container, refrigeration units,... Before realizing something practical, one will always make a 3D design, as in the example below. This realised setup produces 864 kg of hydrogen per day.

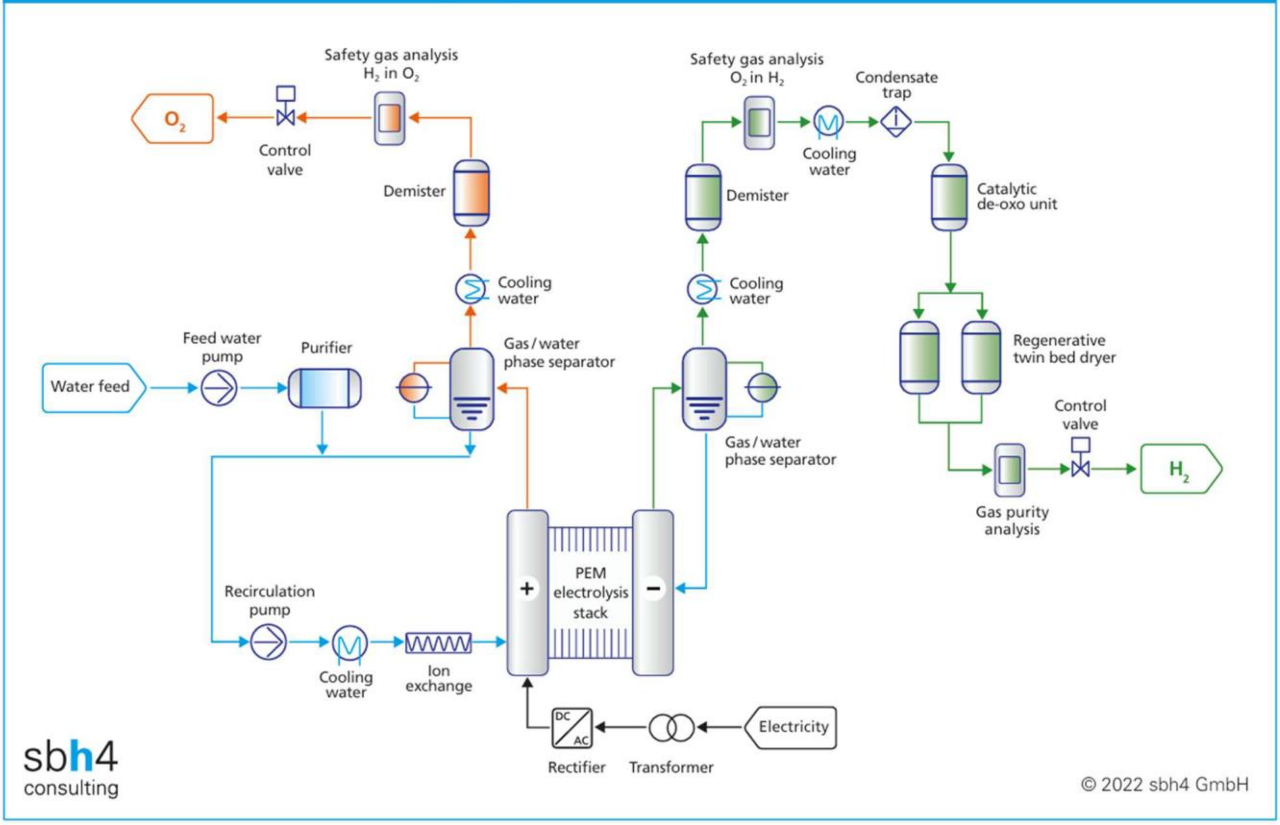




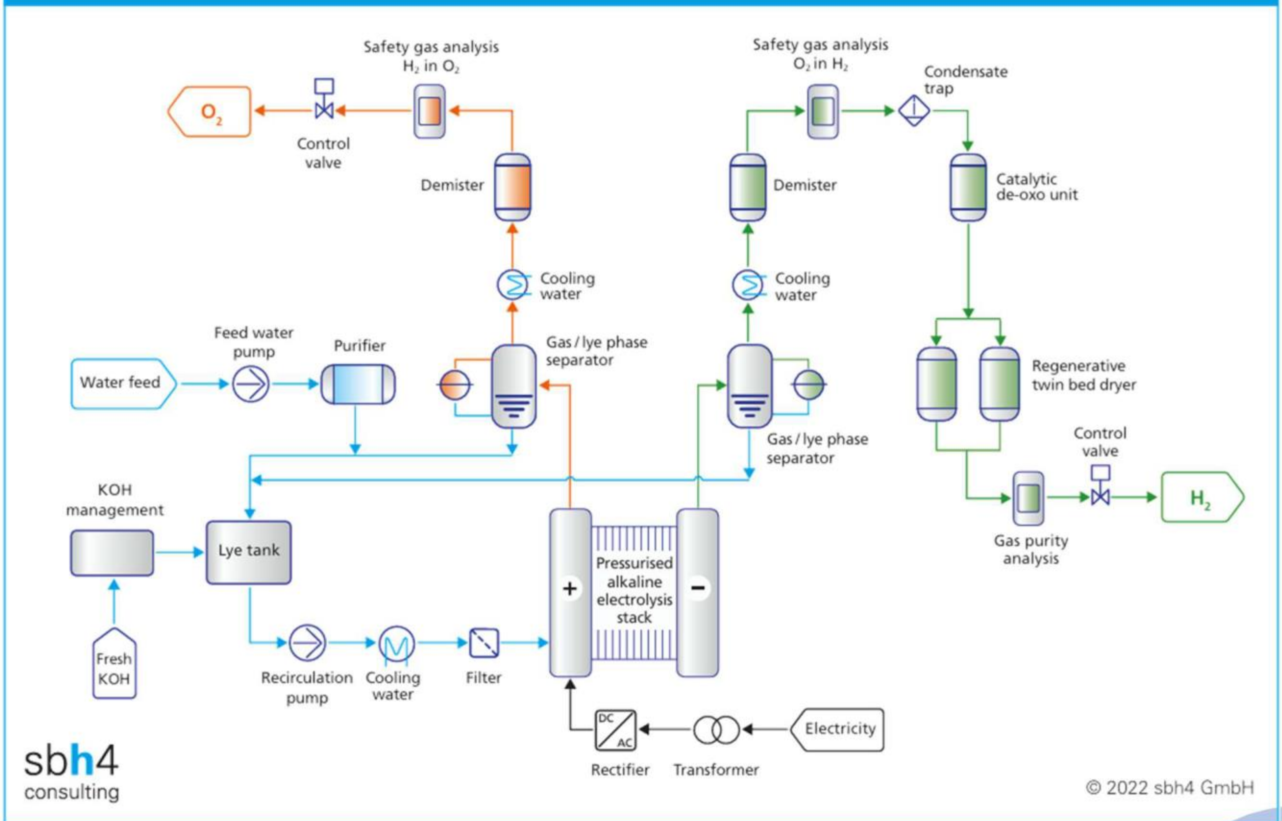
Overview of a Process Container with a HyLYZER® 500 PEM Electrolyser

The next page shows schematic processes of AEC and PEM. Look for the differences and also note the different advantages and disadvantages. Tip: additional information can be found on the internet.

Pressurised PEM electrolysis process



Pressurised alkaline electrolysis process



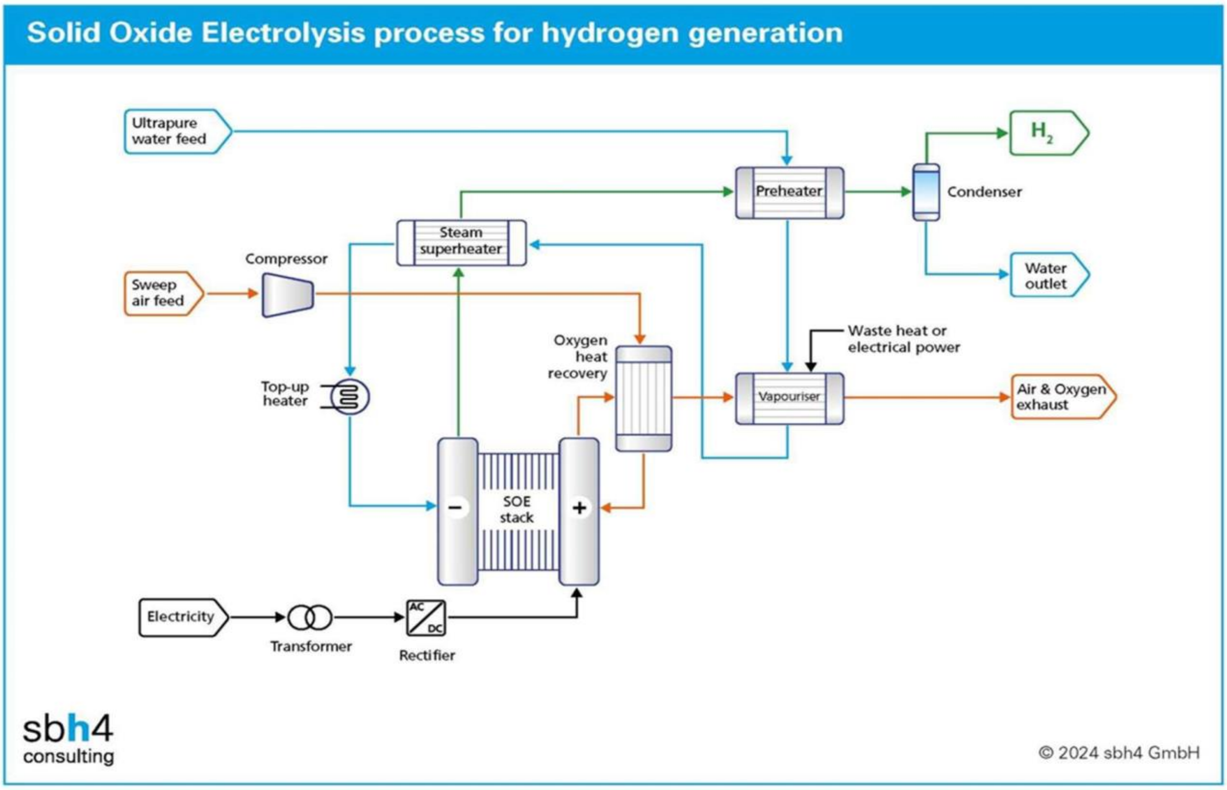
The **efficiency** of an electrolyser is of great importance with regard to the cost. Hydrogen gas is an energy source, but energy must also be invested in it to produce it.

A kg of hydrogen contains 39.4 kWh of energy, in a standard electrolysis system it takes 52.5 kWh of energy to produce this kilo. This means that there is an average return of 75%. About a quarter of the energy is lost in the process.

At a low current, there are fewer flow resistances of the ions through the electrolyte and at a high temperature, the reactions are faster. In short: the lower the current and the higher the temperature = better efficiency.

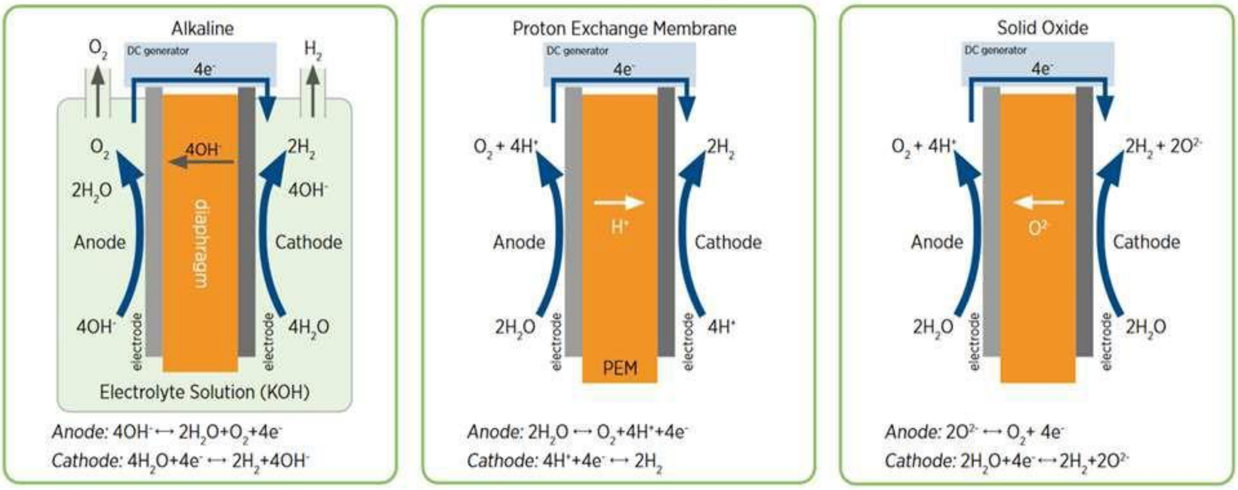
Electrolytes are characterized by the temperature at which they are used. Low-temperature electrolysis (**LTE)** is referred to as AEC and PEM.

There is also **HTE** = high temperature electrolysis. This is called solid oxide electrolysis or **SOE**. For now, this is still in an advanced R&D stage and products are not yet commercially available. The benefits are expected to be increased conversion efficiency and the possibility of producing a syngas directly from steam and CO2, for use in various applications such as synthetic liquid fuels.



Process of SOE – electrolysis.

High-temperature electrolysis is particularly interesting when there is a heat source in addition to electrolysis. It is then economically more efficient than low-temperature electrolysis. Some of the energy is now supplied as heat, which is either free or cheaper than electricity, and in addition, the electrolysis reaction is more efficient at higher temperatures.



Schematic representation of AEC – PEM – SOE.

Place the correct name with the following performances: PEM – AEC – SOE.
What is the difference of parts, materials, operation,...?
Tip: additional information can be found on the internet.

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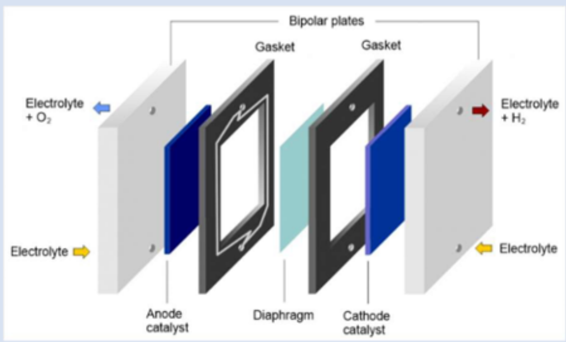
<tr><td rowspan="6">
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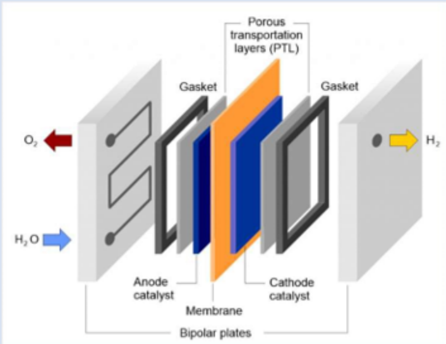
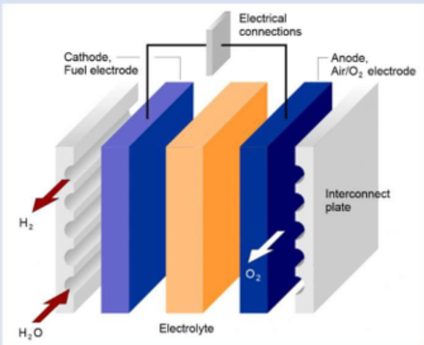
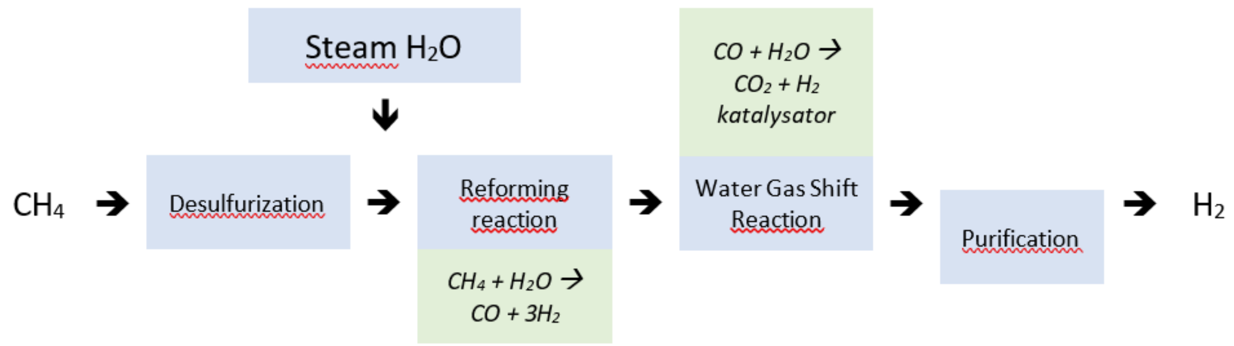




6.2 Steam methane reforming

To produce grey and blue hydrogen, **Steam Methane Reforming** (SMR) is used in which natural gas, or methane (CH4), reacts at high temperature with water (H2O) in the form of steam, usually in the presence of a catalyst such as nickel.

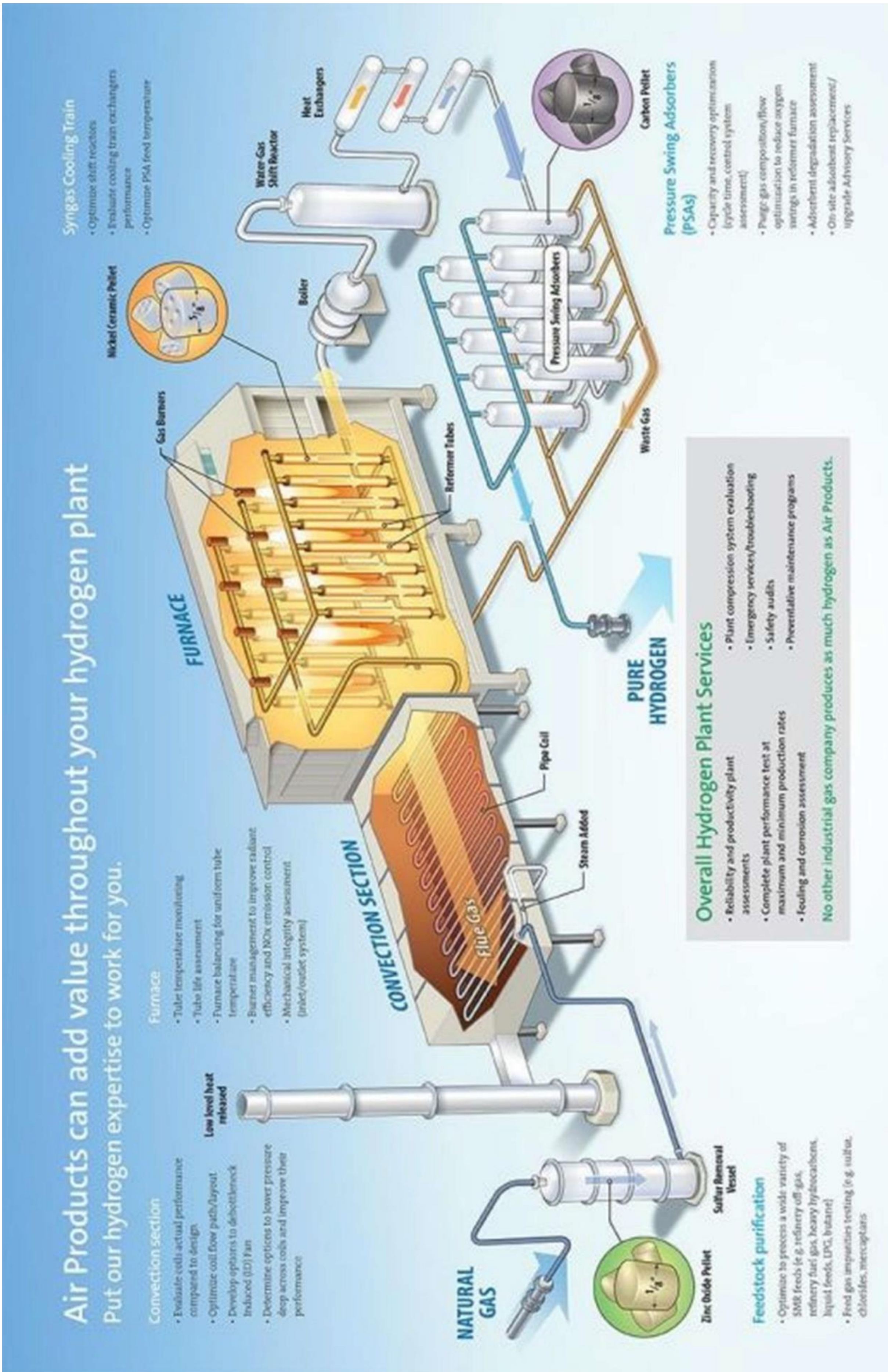
This reaction produces carbon monoxide (CO) and hydrogen (H2), with an additional reaction step between the carbon monoxide and steam bringing further hydrogen and carbon dioxide (CO2). This carbon dioxide causes emissions in gray hydrogen, making this method not ideal for the growing market demand. With blue hydrogen, the carbon dioxide produced is captured and then stored or processed, which results in less, or even no direct emissions at all.



Simplified process of steam methane reform.

Given the delicate balance of incoming flows at Steam Methane Reforming, it is important that the process is safe and predictable. The presence of unwanted particles can have negative consequences for both the components within the SMR installation and for the efficiency of the entire process. Filters are therefore invaluable. This also involves the fact that the process takes place under pressure and elevated temperatures, which creates an aggressive and challenging environment due to the presence of ultra-pure water as input.

On the next page, you see an Overview of an SMR process in the industry.



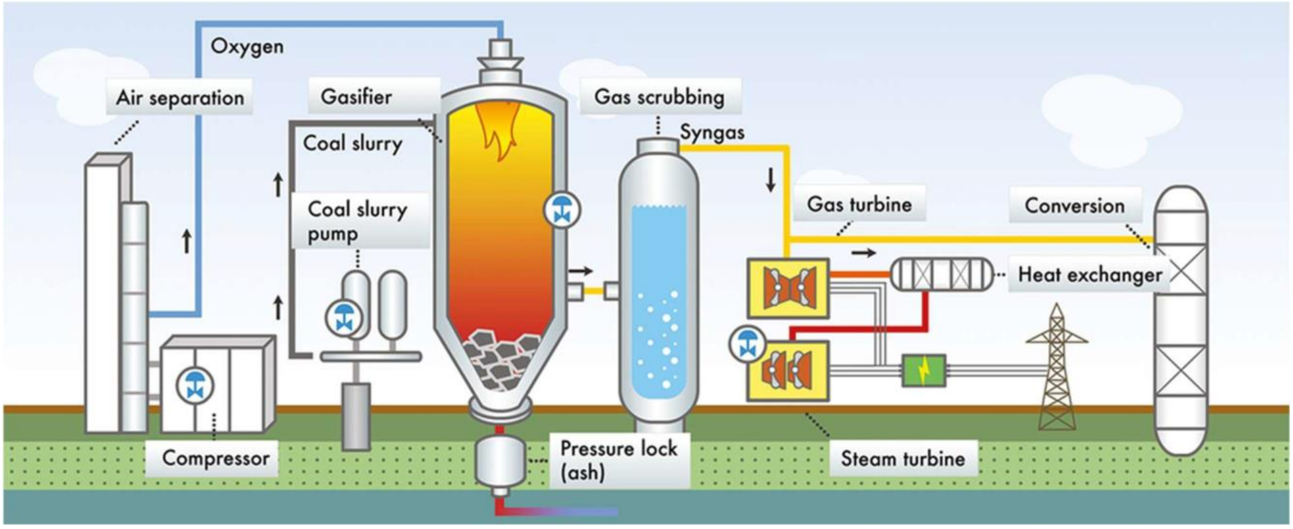
Air Products can add value throughout your hydrogen plant
Put our hydrogen expertise to work for you.
Convection section
• Evaluate coils actual performance compared to design
• Optimize coil flow path/layout
• Develop options to debottleneck Induced (ID) Fan
• Determine options to lower pressure drop across coils and improve their performance
Low level heat released
Furnace
• Tube temperature monitoring
• Tube life assessment
• Furnace balancing for uniform tube temperature
• Burner management to improve radiant efficiency and NOx emission control
• Mechanical integrity assessment (inlet/outlet system)
FURNACE
Gas Burners
Nickel Ceramic Pellet
Syngas Cooling Train
• Optimize shift reactors
• Evaluate cooling train exchangers performance
• Optimize PSA feed temperature
Water-Gas Shift Reactor
Boiler
Heat Exchangers
CONVECTION SECTION
Flue Gas
Reformer Tubes
NATURAL GAS
Pipe Coil
Steam Added
Pressure Swing Adsorbers
Zinc Oxide Pellet
Sulfur Removal Vessel
PURE HYDROGEN
Waste Gas
Carbon Pellet
Feedstock purification
• Optimize to process a wide variety of SMR feeds (e.g. refinery off-gas, refinery fuel gas, heavy hydrocarbons, liquid feeds, LPG, butane)
• Feed gas impurities testing (e.g. sulfur, chlorides, mercaptans
Overall Hydrogen Plant Services
• Reliability and productivity plant assessments
• Complete plant performance test at maximum and minimum production rates
• Fouling and corrosion assessment
• Plant compression system evaluation
• Emergency services/troubleshooting
• Safety audits
• Preventative maintenance programs
No other industrial gas company produces as much hydrogen as Air Products.
Pressure Swing Adsorbers (PSAs)
• Capacity and recovery optimization (cycle time, control system assessment)
• Purge gas composition/flow optimization to reduce oxygen swings in reformer furnace
• Adsorbent degradation assessment
• On-site adsorbent replacement/ upgrade Advisory Services

6.3 Coal gasification

The process starts with gasification. This involves converting coal into a very hot (up to 1800°C) synthesis gas, or **syngas**, which consists mainly of carbon monoxide, hydrogen gas and carbon dioxide, along with small amounts of other gases and particles. This is done by mixing finely ground coal with an oxidant, usually steam, air or oxygen.

The syngas is then cooled and cleaned to remove the remaining gases and particles, leaving only carbon monoxide, carbon dioxide and hydrogen. Syngas is easier to clean than the emissions of a conventional coal-fired power plant. During the cleaning of the syngas, mercury, sulphur, trace impurities and particulate matter are removed.

The cleaned syngas is then led to a shift reactor. During this reaction, carbon monoxide is converted into additional hydrogen and carbon dioxide by mixing it with steam. After this step, the syngas consists mainly of hydrogen and carbon dioxide. Finally, the syngas is separated into streams of hydrogen and carbon dioxide. After the hydrogen has been further cleaned, it is ready for use.



Overview of a coal gasification in industry.

6.4 Biomass gasification

Gasification is a process that converts organic or fossil carbon-containing materials into carbon monoxide, hydrogen and carbon dioxide at high temperatures above 700°C, without combustion, with a controlled amount of oxygen and/or steam.

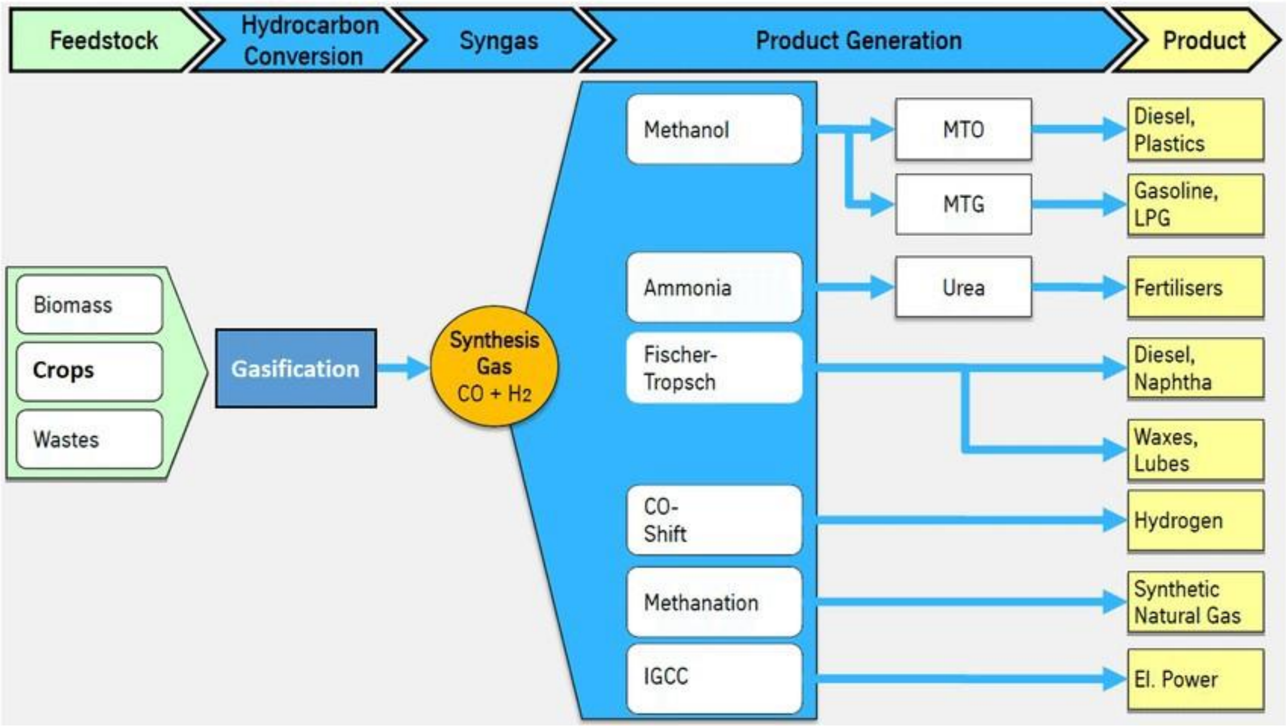
The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas-shift reaction (= CO + H2O → CO2 + H2 + small amount heat). Adsorbents or special membranes can separate the hydrogen from this gas stream.

A simplified example reaction: C6H12O6 + O_2 + H2O → CO + CO2 + H_2 + other compounds. In this reaction, glucose is used as a substitute for cellulose. Actual biomass has a highly varying and complex composition in which cellulose is one of the most important components.

This process is also referred to as pyrolysis instead of gasification. This is the gasification of biomass in the absence of oxygen.

Automatic Industrial Biomass Pyrolysis Gasifier.

In general, biomass is more difficult to gasify than coal, and it produces other hydrocarbon compounds in the gas mixture that leaves the gasifier; This is especially true when there is a
no oxygen is used. As a result, an extra step is often required to convert these hydrocarbons with a catalyst into a syngas mixture of hydrogen, carbon monoxide and carbon dioxide. As in the gasification process for hydrogen production, the carbon monoxide is converted into carbon dioxide in a shift reaction step (with steam). The hydrogen produced is then separated and purified.



Gasification of biomass into synthesis gas can be used in various applications (Fig. Radtke and Wulcko 2015)

6.5 Thermochemical water splitting

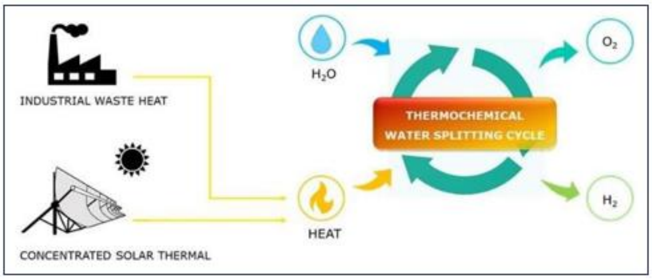
Thermochemical water splitting uses very high temperatures, generated by concentrated solar energy or waste heat from nuclear reactors, to split water into hydrogen and oxygen. This technology offers a promising longer-term solution for hydrogen production with potentially low or no greenhouse gas emissions.

The process uses temperatures between 500°C and 2,000°C to cause a series of chemical reactions that produce hydrogen. One of the most important features of this system is that the chemicals used are used over and over again, resulting in a closed loop. As a result, the process only consumes water and produces hydrogen and oxygen as end products.

The required temperatures can be achieved in 2 ways:

- Concentrated **solar energy**: With the help of mirrors, so-called heliostats, sunlight is concentrated on a central reactor. Sufficient heat is generated to support chemical reactions.
- **Waste heat** from nuclear reactors: The heat released from advanced nuclear reactors can be used to provide the high temperatures required for the water splitting process.

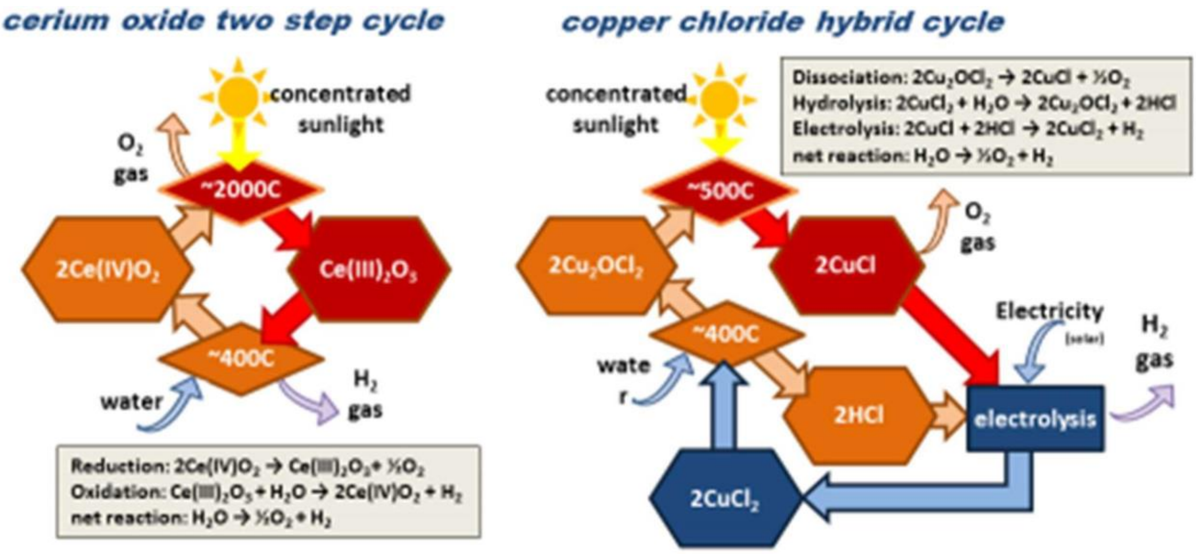
Setting up heliostats in South Africa.



More than 300 different thermochemical water splitting cycles have already been investigated, each with their own operational conditions, challenges and opportunities for hydrogen production.

These cycles vary in complexity and efficiency depending on the chemical processes used and the technology required to generate the required heat.

Two well-known examples of thermochemical water splitting are the **direct** two-step cerium oxide cycle and the **hybrid** copper dichloride cycle. Direct cycles are usually simpler because they involve fewer steps, but they require higher temperatures to function. Hybrid cycles are more complex and require more steps, but can operate at lower temperatures, which makes them more suitable for certain applications.



Schematic representation of thermochemical water splitting.

6.6 Hydrogen as a by-product

Hydrogen as a **by-product** is an interesting and cheap source of hydrogen. Electrochemical processes such as the industrial production of caustic soda and chlorine produce hydrogen as **a waste product**.

It is created by an electric current through a solution of salt – sodium chloride in water (= popularly called **brine).** This product separates and recombines chlorine gas, dissolved caustic soda and hydrogen by exchanging electrons.

Due to the nature of the chemical reaction, the chlorine, the caustic soda and the hydrogen are always manufactured in a fixed ratio: 1.1 tons of caustic soda and 0.03 tons of hydrogen per ton of chlorine.

We have discovered different methods for the production of hydrogen. Some have not been discussed but additional information can be found on the internet. Put the correct name with the concise statement: alkaline electrolysis | SOEC Electrolysis | AEM Electrolysis | PEM Electrolysis | PEC electrolysis | thermochemical fission |biological hydrogen production.

	This technology uses a conductive solution of potassium or sodium. The electrolysis process takes place in a cell where water is split into hydrogen and oxygen by means of an electric current. These electrolysers are known for their robustness, reliability and long service life.
	This technology operates at high temperatures (700-1000°C) and uses ceramic material as a current conductor. This technology is very efficient because it uses heat that can be reused within the system. It is especially suitable for industrial applications where high temperature heat is already available.
	A technology with a combination of alkaline and PEM technology. The use of non-precious metals reduces costs. This technology is still under development but has potential for lower costs and improved efficiency.
	This technology uses a proton conductive membrane to split water into hydrogen and oxygen. These electrolysers have a compact and flexible design, making them suitable for dynamic applications where a rapid response to changes in the power supply is required. They are often used for applications where high purity of hydrogen and fast start-up and shutdown time are required.
	This technology uses solar energy to split water into hydrogen and oxygen, without the intervention of electricity. These cells are made up of semiconductors that absorb light and use the energy to split water. This technology is attractive because of the direct use of solar energy, but it is still in the early stages of development.
	It uses thermochemical cycles, splitting water through chemical reactions driven by heat, often from solar or nuclear sources. An example is the Sulfur-Iodine (S-I) cycle, which requires very high temperatures (above 800 degrees Celsius). This method has a lot of potential for efficient hydrogen production, but still requires a lot of research and development.
	This process uses microorganisms such as algae and bacteria that can produce hydrogen biologically. Under certain conditions (e.g., in the absence of sulfur), some microalgae can produce hydrogen through natural photosynthesis. This production is an interesting and sustainable option, but scalability and efficiency still need to be significantly improved.

7. COMPARING DIFFERENT PRODUCTION MEHODS

The different production methods of hydrogen can be compared in different ways.

Our comparison is based on:

- Impact on the environment
- Energy efficiency
- Economic viability
- Technological maturity.

Due to the rapid advancement of technology, this is likely to change very quickly and hopefully for the better.

7.1 Impacting the environment

The main **indicators** of environmental impact in life cycle assessments are:

- acidification potential (AP)
- potential for global warming (GWP)
- abiotic depletion potential (ADP)
- human toxicity (HTP)
- eutrophication potential (EP).

In this study, the focus is on GWP, due to **greenhouse gas emissions** from hydrogen production, together with ADP (fossil fuels) and AP, to assess fossil fuel consumption and acidifying emissions respectively.

Different literature sources report varying values for these indicators, especially in clean energy hydrogen production. This is due to the limited application of some techniques, which leads to variations in inventory data.

To circumvent this uncertainty, we present minimum, average, and maximum results for hydrogen production methods. Some technologies, such as microbial hydrogen production, are missing from this analysis due to limited life-cycle data.

H_2 productie proces	AP (g SO eq)			GWP (kg CO_2 eq)		
	Average	Min.	Max.	Average	Min.	Max.
SMR involving CCS				3.70	3.90	3.70
Steam methane reforming SMR	15.20	8.40	28.90	11.98	10.56	13.80
Coal Gasification (CG) involving CCS				4.87	4.14	7.14
Coal gasification	59.70	11.00	139.00	22.99	19.42	25.25
Biomass gasification (BG)	22.50	14.50	37.10	3.54	2.67	4.40
Electrolyse via wind	4.30	0.20	11.80	1.08	0.03	2.21
Electrolyse via biomass	29.00			2.70	2.40	3.00
Electrolyse via solar	6.10	2.10	8.10	1.82	0.37	2.50
Electrolysis (high temp. via nuclear)	4.40	3.40	4.80	1.24	0.42	2.00
Sulphur – iodine (S– I) cycle (via nuclear)	3.40	2.40	4.30	0.64	0.41	0.86

Copper – chlorine (Cu-Cl) via grid	91.70	76.60	99.50	14.67	12.30	15.90
Copper – chlorine (Cu-Cl) via nuclear	6.20	2.80	9.60	0.92	0.56	1.35
Methanol reforming	17.00			17.90		
Ethanol reforming	32.00			12.20		

Source: Nnabuife, S.G.; Darko, C.K.; Obiako, P.C.; Kuang, B.; Sun, X.; Jenkins, K. A Comparative Analysis of Different Hydrogen Production Methods and Their Environmental Impact. Clean Technol. 2023, 5, 1344–1380.

What can **conclusions** be drawn from the table? Fossil fuel-based methods (= CG and SMR) have the highest AP – and GWP – values, although carbon capture and storage (CCS) can significantly reduce emissions.
CCS (carbon capture and storage) can reduce the potential for global warming (GWP) by 71.7% for CG and 69.1% for SMR, depending on the efficiency of CO2 capture.

The ADP of hydrogen production from fossil fuels is high, as these fuels provide both energy and feedstock. SMR is relatively more efficient with energy consumption between 183.2 and 198.4 MJ, while CG is between 213.8 and 333.2 MJ.

Alternative methods, such as electrolysis based on renewable energy, have lower ADP values and less impact on the environment. Biomass gasification has a moderate impact, higher than electrolysis, but lower than fossil methods.

The GWP of electrolysis depends heavily on the energy source: when using grid power, AP and GWP can even be higher than with CG and SMR. Renewable energy sources such as solar, wind or nuclear power significantly reduce these values. It is therefore **essential to combine** electrolysis systems with **clean energy**.

7.2 Energy efficiency

Most commercial hydrogen (H_2) worldwide is currently produced via steam methane reforming (SMR), where natural gas (methane) reacts with steam, producing H_2 and CO_2. Although SMR is a common and cost-efficient method, it is not very energy efficient due to the high carbon content of methane. The total energy efficiency of SMR is typically between 65 and 75%.

In electrolysis, water molecules are split into H_2 and O_2. This process is environmentally friendly, but the energy efficiency depends on the energy source used. Renewable energy can achieve an efficiency of 70–80%, while electricity from fossil fuels reduces efficiency to 50–60%.

Biomass gasification converts organic material, such as wood or waste, into a mixture of H_2, CO and CO_2, which can be further processed into pure H_2. Although this method is renewable and carbon-free, the energy efficiency usually ranges between 40 and 60%, with advanced systems reaching almost 70%.

In summary, SMR is the most commonly used, but less energy-efficient method. Electrolysis is more efficient, especially with renewable energy, while biomass gasification offers a sustainable option with typically lower efficiency.
Improving energy efficiency remains a key objective for future H_2 production.

7.3 Economic viability

The costs of producing, using, transporting and storing hydrogen (H_2) play a crucial role in the economic evaluation of H_2 energy systems. The cost of primary energy sources currently largely determines the importance of H_2 production. Hydrogen production methods based on renewable energy are currently more expensive than those based on fossil fuels, mainly due to the cost of electricity that has a major impact on hydrogen production from non-fossil sources.

Electrolysis is the most commonly used technique to produce hydrogen from non-fossil fuels. The cost of electrolysis is influenced by the price of the electrolyser and its use of it. Despite the fact that electrolysis does not cause CO_2 emissions, the cost of green electricity remains higher compared to fossil fuels. Factors such as pressure change absorption and catalyst costs increase the price of thermochemical methods, while reduced biomass costs and improved efficiency can optimize production.

Economically, electrolysis is a suitable option for small-scale hydrogen production, but large-scale production increases costs due to high electricity consumption. The cost of hydrogen production via photochemical and dark fermentation techniques is between USD 2.5 and 2.8 per kg, while the cost of these techniques in 2017 was estimated at USD 18.7 and 3.7 per kg, respectively.

In Australia, the cost of H_2 production via steam methane reforming is between AUD 1.88 and 2.30 per kg, and via coal gasification between AUD 2.02 and 2.47 per kg. Alkaline electrolysis costs AUD 4.78 to 5.84 per kg, while proton exchange membranes cost AUD 6.08 to 7.43 per kg.

Production via partial methane oxidation with synthesis gas costs EUR 1.33 per kg H_2. The cost of hydrogen production from natural gas is between USD 0.37 and 1.82 per kg, and USD 2.48 to 3.15 per kg from coal. Despite high costs for wind and solar energy from 2011 to 2016, the hydrogen market was predicted to grow by 6.21% during this period, from USD 87.3 to 118 billion. Biomass gasification and pyrolysis produce H_2 at prices of USD 8.91 to 5.51 per GJ and USD 10 to 14 per GJ, respectively.

Method	Production costs (USD per kg)	Source
Photo-catalytic H2O splitting	5.00	Solar
Steam reforming	0.75	Methane
Centralised biomass gasification	1.20 → 2.40	Biomass
Gasification without CO2 sequestration	0.92	Coal
Electrolysis	2.60 → 3.00	Nuclear
H2O splitting	1.40 → 2.30	Nuclear

Overview with pricing in 2023.

According to the table above, the cost of steam methane reforming (USD 0.75 per kg) is significantly lower than other H_2 production techniques. Solar electrolysis is currently the most expensive method (USD 5.0/kg), but with technological advancements, these costs can decrease, making this method more sustainable and economically advantageous in the long run.

The commercialization of these methods is expected to increase in the future, and due to their minimal impact on the environment, the cost of hydrogen production is expected to be comparable or lower than that of traditional fossil fuel-based techniques.

7.4 Technological maturity

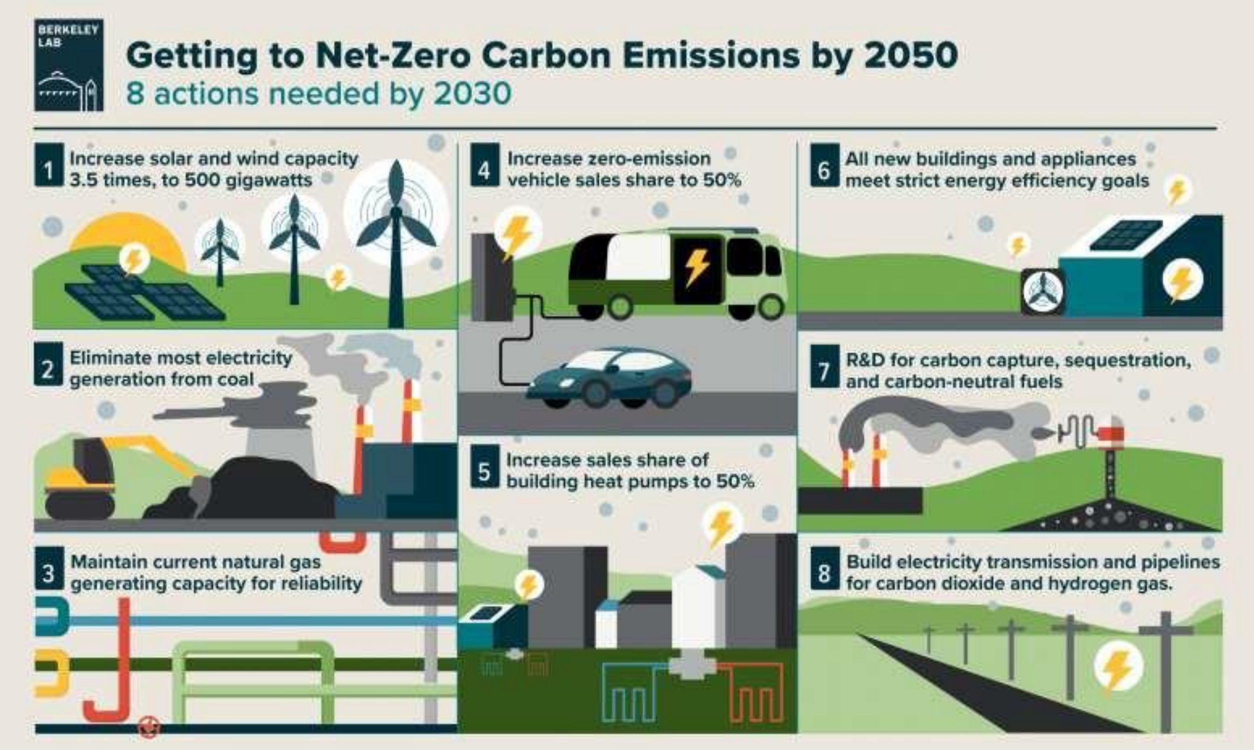
The current production of low-emission hydrogen (H_2) is significantly lower than what is needed to meet the global goals of the NZE (Net Zero Emissions) – and AP (acidification potential) – scenarios. Nevertheless, many projects have been announced to increase the production of low-emission H_2.

If all projects are completed as planned, 24 Mt of low-emission H_2 could be produced annually by 2030. About 50% of this would come from G7 countries.

According to estimates, a quarter of the required low-emission H_2 scenario for the NZE 2050 scenario would be covered by the announced projects, while 80% of the AP needs would be met. However, many of these projects are delayed by challenges such as a lack of demand, regulatory and accreditation uncertainty, and a lack of infrastructure to get H_2 to end users. Developing countries in particular, which account for a quarter of potential production, are struggling with additional problems such as a shortage of trained personnel and financing. Without appropriate policy measures, production is expected to be limited to 6 Mt in 2030.

Only 4% of current projects are at an advanced stage, i.e. under construction or with a final investment decision (FID). About a third of the projects are still in the concept phase, while the rest are in the feasibility or engineering phase. About 2% of the CCU (carbon capture and utilisation) projects, accounting for 0.2 Mt H_2 production in 2030, are almost complete. Only 5% of electrolysis projects are well advanced, accounting for around 0.7 Mt H_2, while the majority of potential production is still in the planning or feasibility phase. Large projects can take up to a decade to realize.

In 2021, more than 80% of H_2 production by G7 countries came from CCU fossil fuel projects and 20% from electrolysis. By 2030, G7 could produce up to 8.5 Mt of low-emission H_2, given the large number of projects still in the feasibility and engineering phase. G7 countries therefore play a crucial role in the rapid development of low-emission H_2 production.



Action plan by 2030 with the ultimate goal in 2050: 0% CO2 emissions.

8. STORAGE OF HYDROGEN

One of the most important things we have to take into account when we really want to integrate hydrogen into the current (gas) network is **storage** and distribution.

How are we going to supply millions of households and businesses with hydrogen?

After production, it is important that hydrogen is stored safely and efficiently.

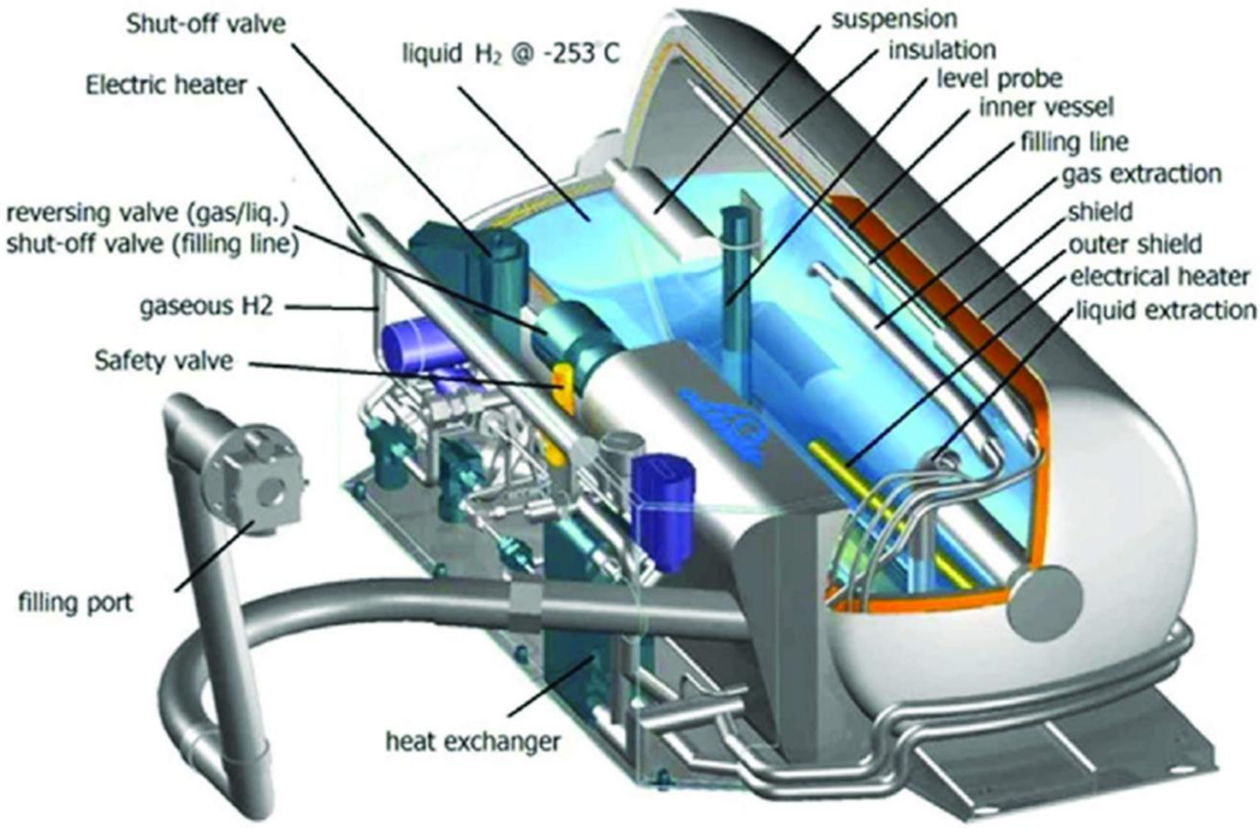
The most **common** methods are in gaseous form, liquid state, as a gel or in powder form.

Storing hydrogen as **a gas** is the most common form. After the electrolysis of hydrogen, hydrogen gas **is released immediately**. In order to store hydrogen gas as efficiently as possible, we will compress it to save space so that more gas can be stored in the tank.

Hydrogen gas is often stored in **high-pressure composite vessels** . The hydrogen is compressed to 200, 350 or sometimes up to 700 bar to limit space. This sounds efficient, but there is a big disadvantage. By compressing hydrogen, about 6-15% of the hydrogen energy is lost, depending on how hard it is compressed.

Liquid storage of hydrogen first is also becoming increasingly popular. The advantage is that liquefied gas always takes up less space than normal gas. But there are still quite a few snags. For example, you first have to cool hydrogen gas to -253°C before it can be in a liquid state. Obviously, this takes a lot of energy. For example, it has been calculated that you need about 1/3rd of the energy content of the tank to cool hydrogen.

In addition, after 14 days, **energy is lost** in a tank in which liquid hydrogen is transported. This hydrogen gas is then released into the tank, which in turn creates more pressure in the tank. To counteract this, there are valves in the hydrogen tanks, but nevertheless energy loss takes place.

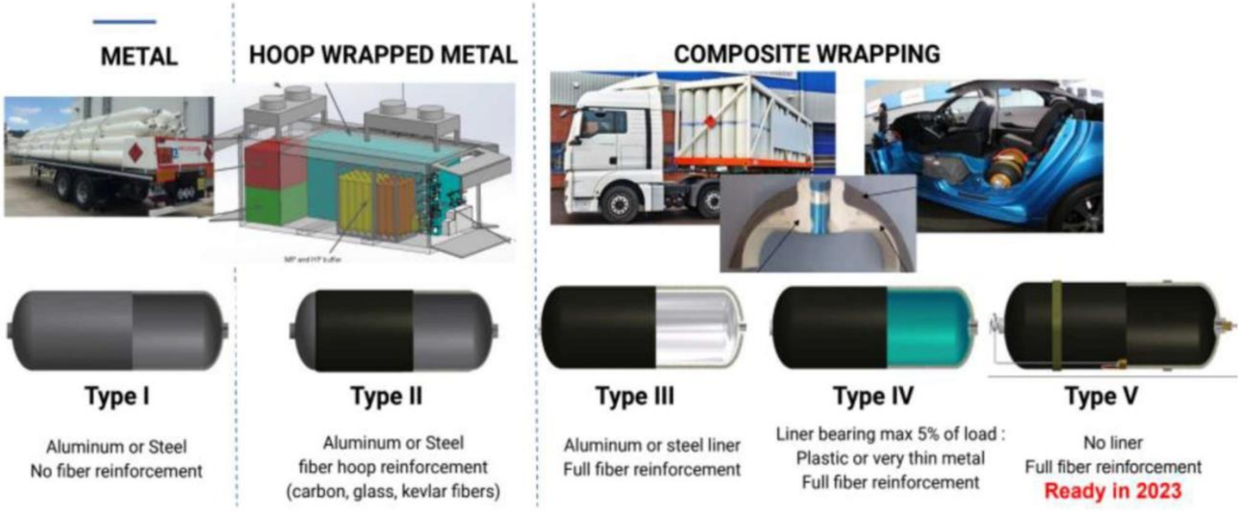


Cross-section of a liquid hydrogen tank.

A brief overview to store hydrogen **safely** :

Properties	Liquid	Gaseous
Pressure	12 to 13 bar	700 to 1000 bar
Temperature	Lower than -253°C	-20°C to +80°C
Density	1.013 bar, -253°C : 70.85 kg/m³	1.013 bar, 0°C : 0.0899 kg/m³ 700 bar, 15°C : 40.2 kg/m³
Challenge	Keeping temperature low!	High pressure! Risk on leakage!

It is therefore important to pay attention to **the construction** of the storage tanks where different types are used.



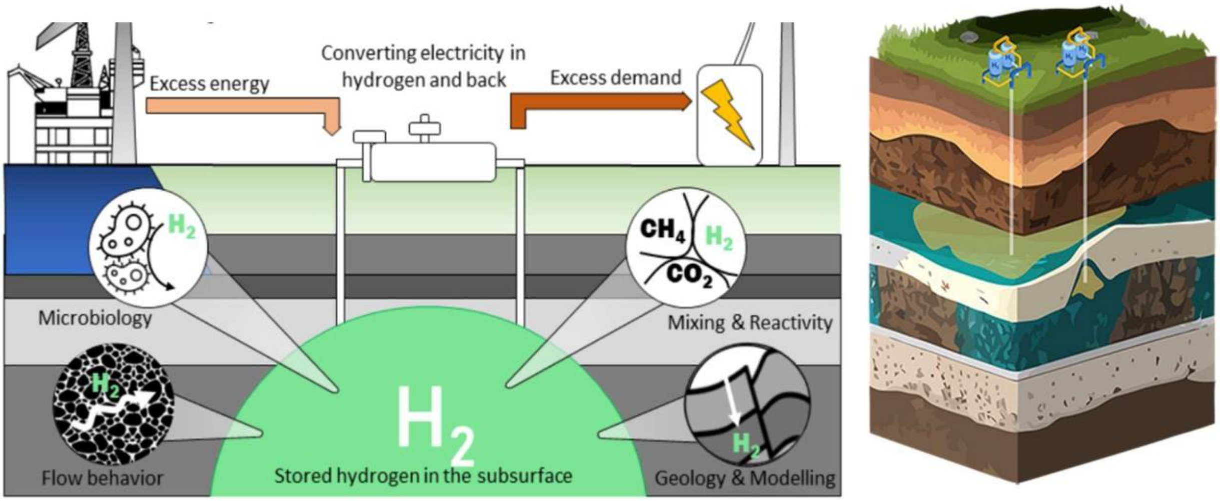
Overview of tanks during transport on our roads.

More information about hydrogen storage
or the construction of a hydrogen tank?
Follow the various links.

Another option is the use of **metal hydrides**, in which hydrogen is bonded to metals or alloys. This system operates at pressures ranging from 10 to 50 bar and temperatures ranging from 20°C to 300°C, depending on the material used. While it provides a safe storage method, the temperature and pressure depend on the chemical properties of the metal.

In addition, hydrogen can be stored in chemical hydrogen carriers, such as liquid organic hydrogen carriers (LOHCs) or ammonia. The storage itself usually requires little pressure and can take place at room temperature, but releasing hydrogen from these carriers often requires temperatures between 25°C and 250°C, depending on the chemical compound.

Finally, there is underground storage, where hydrogen is stored in geological structures such as **salt domes** or empty gas fields. This is usually done at a pressure of 100 to 200 bar and at temperatures of 15°C to 50°C, depending on the depth of the storage site and the geological conditions.



Schematic representation of underground storage and the distribution of different soil layers.

In 2021, the first research was done into storing hydrogen as **gel**. In Germany, researchers have discovered that they can make a hydrogen paste in which hydrogen can be safely supplemented, transported and stored. The production of this hydrogen gel is done by adding magnesium powder to the gas and heating it to 350 degrees. Then ester and metal salt are added, turning it into the so-called "power paste".

What is the use of hydrogen as a paste? First of all, it is a safe way of storing and transporting. The hydrogen can only detach from the paste at temperatures above 250 degrees and is therefore not highly flammable. In addition, this can be an easier way to fill up with hydrogen. You only need to replace the hydrogen paste cartridge and fill the water tank with tap water. This can of course be done on the road, but also at home.

Another option that is increasingly being tested is storing hydrogen as **a powder**. You can do this to fill a barrel with hydrogen, boron nitride (powder) and balls of steel. When you then rotate the vessel, the steel balls will provide pressure on the hydrogen. By letting the barrel tumble for hours, hydrogen in powder form will eventually be formed. The advantage is that hydrogen powder is light, which makes storage easier. In addition, this powder has an unlimited shelf life and there is no energy loss!

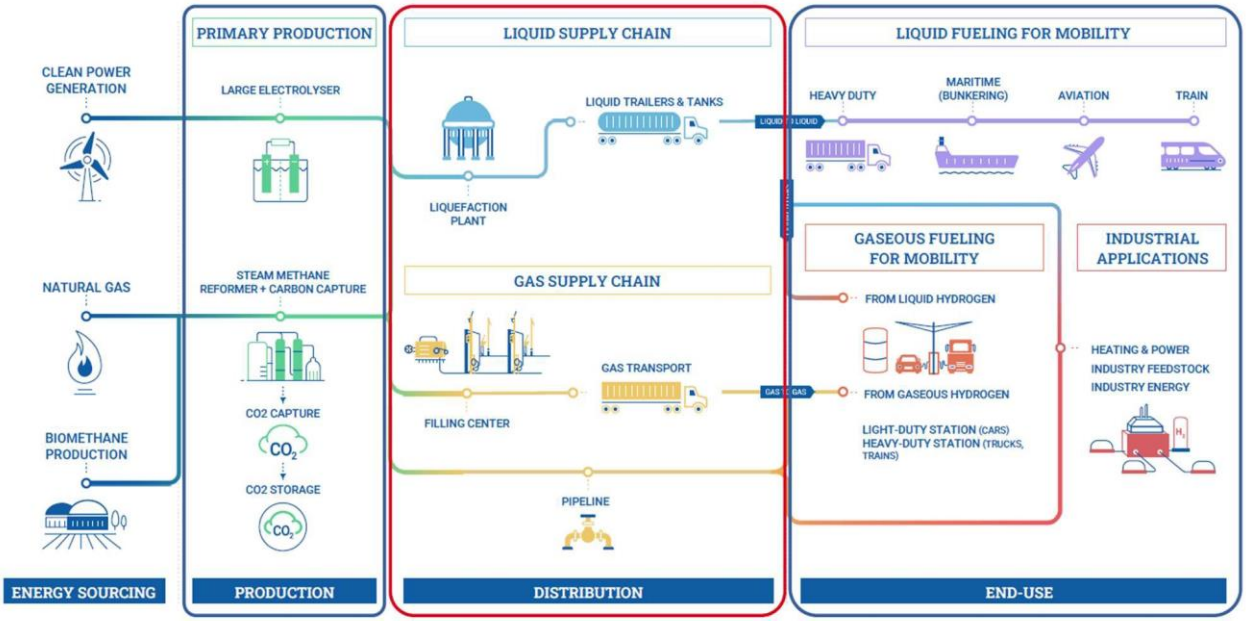
Hydrogen powder has been actively produced in the Netherlands since May 2023. For example, Electriq Global and Zenith Energy have built the first hydrogen powder plant in the port of Amsterdam.

9. TRANSPORT OF HYDROGEN

Hydrogen can be transported over long distances in various formats. The transport of compressed or liquid hydrogen can be done by truck or tankers. Compressed gaseous hydrogen will use pipelines and trucks.

In short, the most common are:

- Compressed gas cylinders or cryogenic liquid tankers
- Pipelines
- Mixing with natural gas



Overview of hydrogen distribution.

9.1 Compressed Gas Cylinders

At the moment, the most common way of hydrogen transport is to transport hydrogen on trucks. Large metal or composite tanks are loaded onto a truck and then brought to location such as hydrogen filling stations.
The **gaseous hydrogen** will be transported in small to medium quantities in compressed gas cylinders by truck. For larger quantities, pressurized gas cylinders are bundled on CGH2 Tube Trailers.

1	Tube trailer for transport of 500 kg of hydrogen at ambient temperature under a pressure of 200 – 250 bar.
2	Container trailer for transport of 1000 kg at ambient temperature under a pressure of 500 bar.

The gas cylinders are usually made of steel and have a high net weight. This can lead to mass-related transport restrictions. The latest pressure storage systems use lightweight tanks for transport by truck.

The low density of hydrogen also has an impact on transport: under standard conditions (1.013 bar and 0 °C), hydrogen has a density of 0.0899 kg per cubic metre (m3). If hydrogen is compressed to 200 bar, the density rises to 15,6 kg of hydrogen per cubic meter, and at 500 bar it reaches 33 kg H2/m3.

Compressed gas cannot be stored as compactly as with a tanker for liquid fuels (petrol or diesel fuel). This means that the available tank volume for hydrogen per tanker is lower. At the moment, about 500 kg of hydrogen is transported by truck, depending on the pressure and container material.

The largest tank volumes for gaseous hydrogen transport are currently 26 cubic metres. Taking into account the low hydrogen density at 500 bar, this results in about 1,100 kg of hydrogen per truck.

Alternatively, hydrogen can be transported in **liquid form** in trucks or other means of transport. This is more cost-effective at greater distances. At a density of 70.8 kg/m3, approximately 3,500 kg of liquid hydrogen or almost 40,000 m3, at ambient pressure, can be transported at a cargo volume of 50 m3.

Liquid trailer for transport of 4000 kg under 1 to 4 bar at a cryogenic temperature.

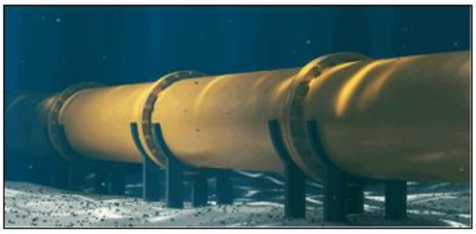
It is also expected that you can transport hydrogen at sea, much in the same way as we do now with oil using large tankers.

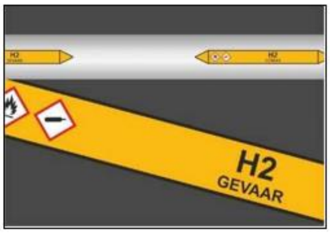
For example, Kawasaki Heavy Industries is developing hydrogen tankers that can transport hydrogen at sea for long distances. These hydrogen tankers were expected to consist of spherical tanks of more than 40,000 m³.

9.2 Pipelines

Transport by truck and ship has an additional disadvantage: extra energy is needed. If pipelines are used , this is not necessary. It is therefore the best option for extensive and large-scale use of hydrogen as an energy source. However, it will be profitable with large volumes of hydrogen. However, there is an opportunity for developing pipeline networks for the distribution of hydrogen to local or regional networks, known as micro-networks. These can then be merged into trans-regional networks.

In 2016, there were already more than 4,500 km of hydrogen pipelines worldwide, the vast majority of which are operated by hydrogen producers (HyARC 2017). The longest pipelines are operated in the US, in the states of Louisiana and Texas, followed by Belgium and Germany.

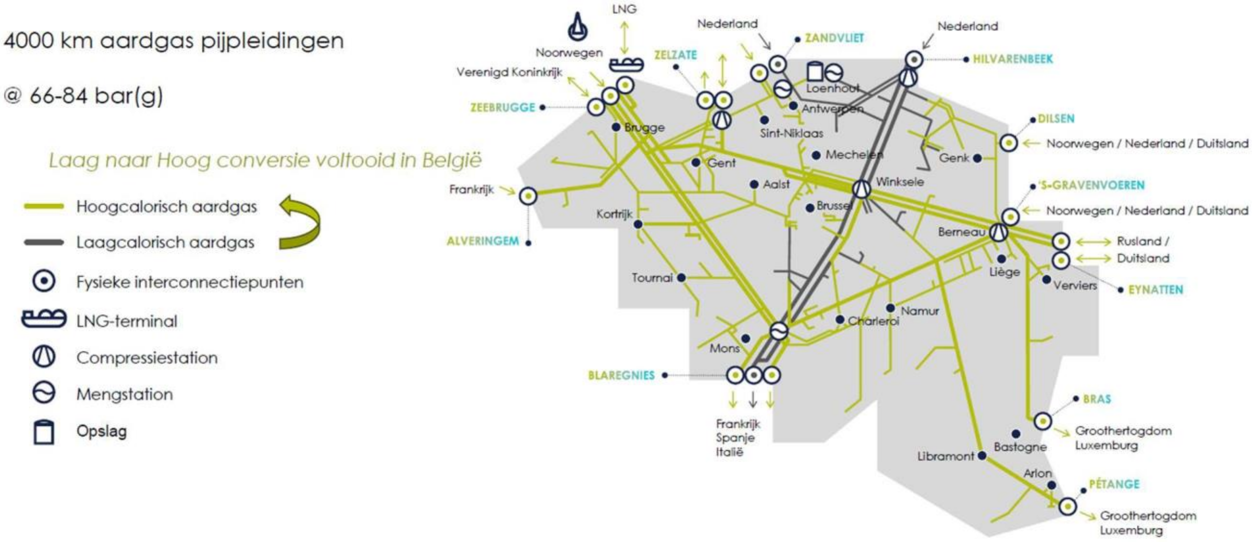




These hydrogen pipelines are part of the millions of kilometres for natural gas around the world. These pipelines transport the gas between cities or between different countries in order to be able to supply more than just the local industry with gas. Existing natural gas pipelines are generally large in diameter and use steel alloys (at high pressure) or materials such as cast iron, copper, steel or plastic (PVC or PE) in the case of distribution pipelines.

However, with increasing sustainability goals and guidelines, the use of natural gas is under pressure. The producers of the pipelines, as well as gas producers and governments, are therefore asking whether the existing infrastructures for natural gas can also be used for a more sustainable gas: sustainable hydrogen.

Research into the best pipelines for gaseous hydrogen has been ongoing for several years and there seem to be opportunities to convert existing infrastructures into a safe hydrogen network. The Netherlands is currently on its way to becoming the first country where the existing natural gas network will be suitable for hydrogen. Adjustments to existing infrastructures such as in average homes will have to be made.



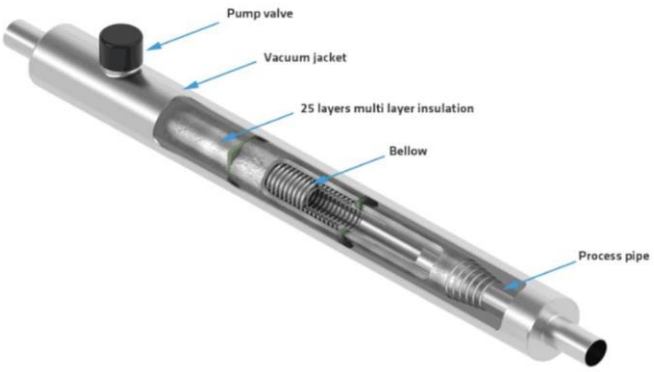
The Fluxys natural gas transmission network in Belgium consists of 4000 km of pipelines.

The transport of gaseous hydrogen is complex, but that of **liquid hydrogen** is even more complex. To prevent waste and ensure optimal safety, transfer lines for liquid hydrogen must be extremely well insulated. Liquid hydrogen has an extremely low temperature of -252.9 °C cold.

Safety is essential when transporting liquid hydrogen. In combination with oxygen, the cryogenic liquid can cause explosions. If ice-cold liquid hydrogen is released due to a leak in the transfer line or if there is insufficient insulation, there is a good chance that the surrounding oxygen will condense. This condensed oxygen in combination with liquid hydrogen can cause dangerous situations.

For this reason, transfer lines for liquid hydrogen are subject to stricter requirements than those for liquid oxygen or liquid nitrogen, for example.

Vacuum insulation (VIP) has proven to be the method for optimal insulation of transfer lines for liquid hydrogen. By providing pipes or systems with a double wall and sucking out all the air between these walls, a high-vacuum environment is created. There are hardly any molecules left in the vacuum, so that no heat transfer can take place from the warm outer tube (*vacuum jacket*) to the cold inner tube (*process pipe*). In this way, a large part of the surrounding heat is kept outside the system or outside the pipe.



Cross-section of a vacuum insulated transfer line.

Vacuum insulated transfer lines have several advantages. Firstly, the high quality of the piping ensures very high efficiency, which means that the long-term operational costs for the system remain lower than those of conventional insulation materials.

Secondly, vacuum insulated transfer lines take up less space than conventional insulation materials (PIR/PUR, Foamglas, Armaflex, Perlite, or Misselon). The double wall offers an insulation value that is so high that it can only be approached with a large number of layers of material with the above materials.

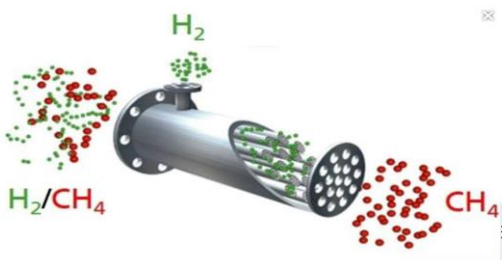
This significantly increases the diameter of the pipe, while also increasing the risk of oxygen condensation as the conventional insulation is less vapour-tight. A safety problem that does not occur with vacuum insulation.

In some specific industries, transfer lines for liquid hydrogen are expected to be equipped with a *double-containment* for extra safety (if the process line gets a leak, there is always the *double-containment* to catch it).

While other insulation methods require the construction of an additional wall to comply with this guideline, vacuum insulation already has two walls. This makes vacuum insulated transfer lines extra safe, extra widely applicable and by far the best choice economically.

9.3 Mixing with Natural Gas

Blending hydrogen in natural gas pipeline networks has also been proposed as a means of supplying pure hydrogen to markets. This in combination with separation and cleaning technologies downstream to remove hydrogen from the natural gas mixture.



It can be assumed that many of the gas transport networks, dist [illegible] e operated in the past are still in use today.

In Leeds, England, the possibility of converting the existing natural gas network in the region (mainly used for the municipal heating supply) to hydrogen has been investigated. Given their length, the large gas networks in many industrialised countries could transport significant amounts of hydrogen.

However, in order to safely integrate hydrogen into existing natural gas pipeline systems, several factors must be evaluated, such as the risk of **brittleness** from hydrogen (Hydrogen Embrittlement = HE).

The most important elements for HE sensitivity are:

- **Intrinsic parameters:** steel microstructure and chemical composition.
- **Environmental parameters:** H2 partial pressure in the pipes, level of voltages and frequencies, size and geometry of existing faults, impurities in transported gas and temperature.

Theoretically, pipelines can handle hydrogen mixtures between 15% and 30% without major modifications without significant negative effects. Although compression of hydrogen can be used for transport and storage, this compression involves an energy loss that can amount to 20% of the energy – content needed for the compression itself.

10. HYDROGEN IN FUEL CELLS

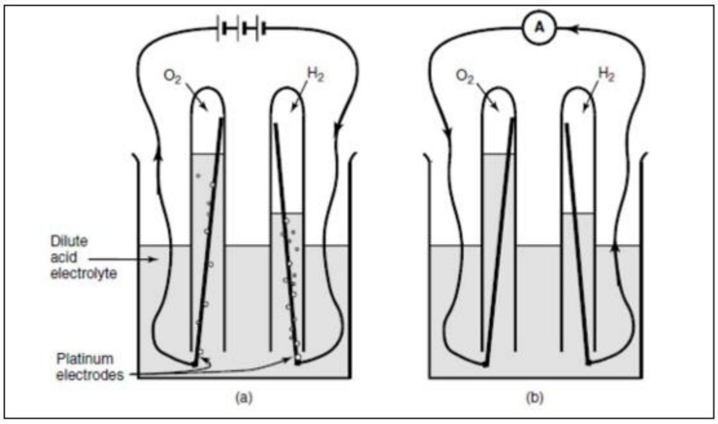
Batteries are not suitable for storing large amounts of electricity for an extended period of time. A major advantage of hydrogen is that it can be produced from surplus renewable energy sources. It can also be stored for a longer period of time.

10.1 Fuel cells: basic theory

The basic operation of the hydrogen fuel cell is simple. The first demonstration of a fuel cell was done by scientist William Grove in 1839, using an experiment according to the setups below.

William Grove (1811 – 1896)

Element of Grove



Schematic experiment van Grove

In setup a, **electrolysis** splits water into hydrogen and oxygen by running an electric current through it. In setup b, the reverse process is depicted. The hydrogen and oxygen react back to water and now an electric current is released. So we can store electrical energy in the hydrogen and take it out again at some point.

The **disadvantage** is that the flows produced are small for the following reasons:

- The small contact area between the gas and the electrode.
- The large distance between the electrodes.

For this reason, electrodes are usually flat (flat or curved), with a thin layer of electrolyte. The structure of the electrode is porous, allowing the gas to penetrate with maximum contact between the electrode, electrolyte, and gas.

To understand how the reaction between hydrogen and oxygen produces an electric current, and where the electrons come from, we need to write out the individual reactions that take place at each electrode. In detail, these vary for different types of fuel cells, so we start with the simplest and still the most common type.

At the anode of a (PEMFC) fuel cell, the hydrogen gases ionize to electrons and H+ ions (or protons).

$$\boxed{2H_2} \longrightarrow \boxed{} + \boxed{}$$

This reaction releases energy. At the cathode, oxygen reacts with electrons coming out of the electrode and the H+ ions coming through the electrolyte. This creates pure water.

$$\boxed{O_2} + \boxed{4e^-} + \boxed{4H^+} \longrightarrow \boxed{}$$

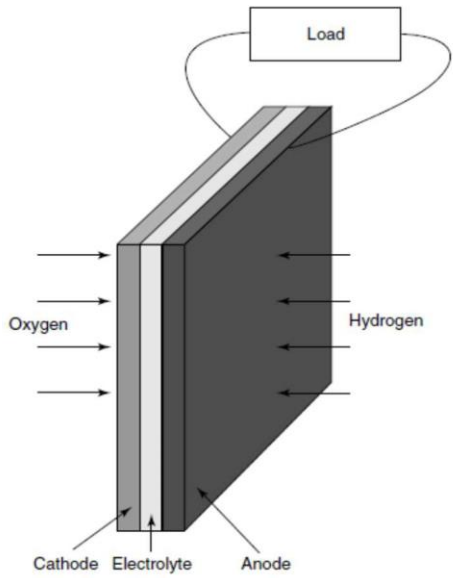
To make the reactions possible, there must be an electrical circuit from the anode to the cathode through which the electrons can flow.

In addition, the H+ ions must pass through the electrolyte. For example, an acid solution with free H+ ions. The same can also be achieved with certain polymers that allow the H+ ions to move.

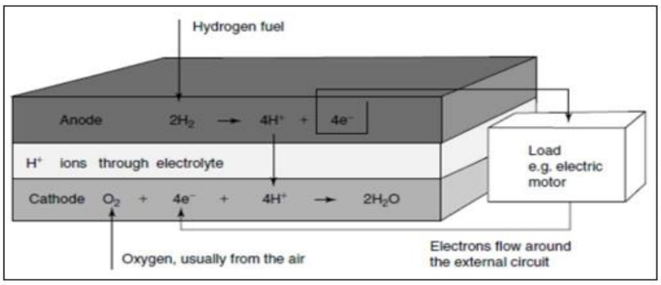
These polymers are also called the proton exchange membrane. In English, this is called Proton Exchange Membrane or PEM.

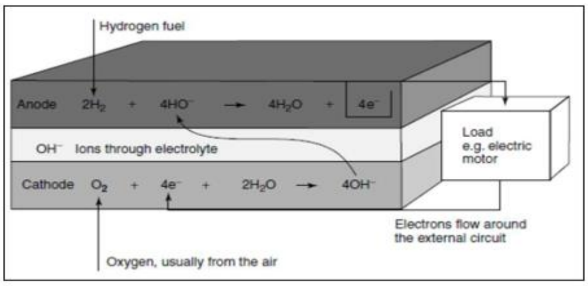
In the above equations we can see that two hydrogen molecules are needed for each oxygen molecule to make the reaction correct, see figure.

It is important to understand that the electrolyte should only allow H+ ions to pass through and not the H2 molecules. Otherwise, there would be no more electric current.



In the figures below, we notice that the electrons flow from the anode to the cathode. Thus, the cathode is the electric Positive, since electron currents run from minus to plus. The cathode, on the other hand, is always the electrode in which the electrons flow, and so the anode is always the electrode from which electrons flow.





This is somewhat confusing but not surprising because the negative electron currents run from minus but plus, and according to the normal definition 'conventional positive current' current runs the other way around: from the positive to the negative pole.

An alkaline fuel cell (AFC) is a fuel cell that uses potassium hydroxide as an electrolyte. The ion transport takes place with the help of hydroxide(OH) ions. The catalyst for the ionization of hydrogen is platinum, or cobalt.