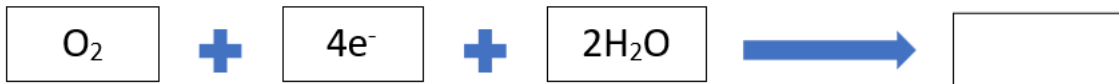


In an alkaline fuel cell, the compound reaction is the same, but the reactions on the electrodes are different. At the anode, these react with hydrogen and electrical energy is released and water is produced.

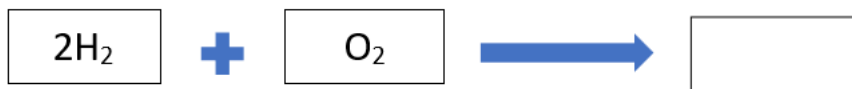


At the cathode, oxygen reacts with electrons from the electrode and the water in the electrolyte and new OH⁻ ions are made.



To achieve this, there must be an electrolyte to allow the OH⁻ ions to pass through and an electrical circuit for the electrons from the anode to the cathode. We also see in the comparisons that twice as much hydrogen is needed as oxygen. In addition, water is absorbed at the cathode but produced twice as fast at the anode.

The compound reaction equation becomes again:



10.2 What is a Bipolar Plate?

Cells can be connected in series **or** in parallel, **just like batteries**. In practice, series connection is often chosen to get the voltage to a sufficiently high level and to reduce the current. The lower the current, the lower the electrical losses.

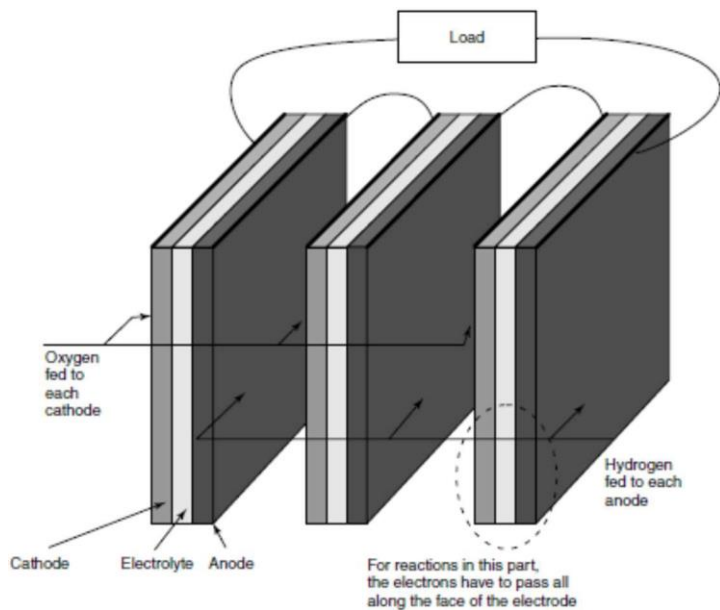


*The difference between a series and a parallel circuit?
Follow the link.*



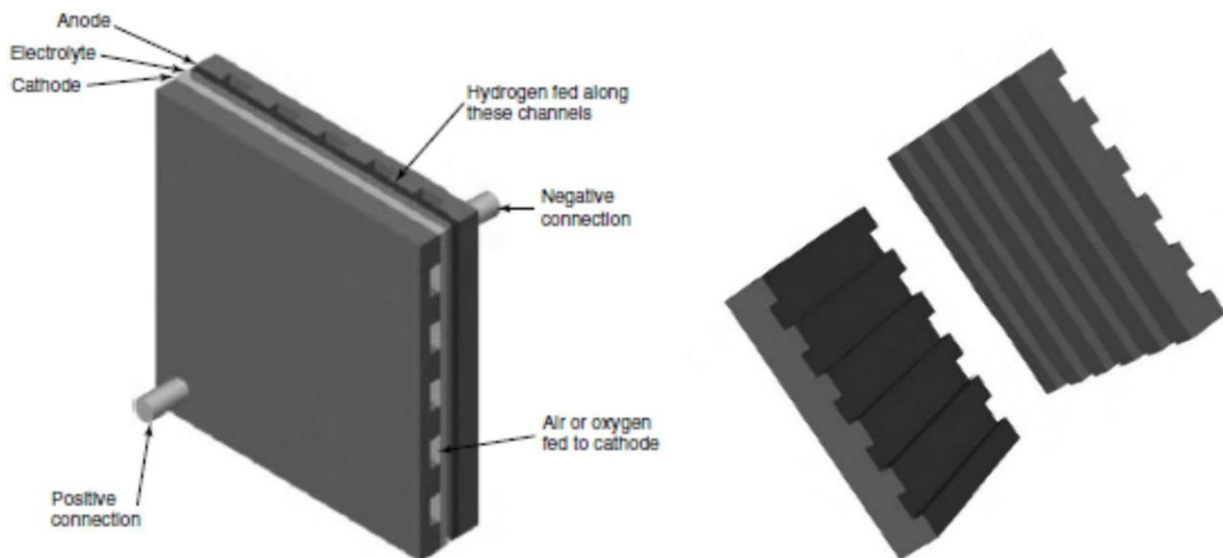
This means that for the production of a useful voltage, the cells are connected in a series. Such a collection of fuel cells in series is called a **stack**. The easiest way is by connecting the edge of each anode to the cathode of the next cell, along the line, as shown in the figure. In this arrangement we see a simplified representation of 3 cells connected in series.

The problem with this method is that the electrons pass through the entire surface of the electrode to the point at the edge where it is connected to the next cell. Although the electrodes are good conductors, an **unwanted loss** occurs here.



A better method of connecting the cell is through the use of a **bipolar plate**. This connects over the surface of a cathode and the anode of the next cell at the same time. The bipolar plate acts as a means of feeding oxygen to the cathode and hydrogen gas to the anode. The two gas supplies must be strictly separated.

The method of connecting to a single cell, across the electrode surfaces, while also supplying hydrogen to the anode and oxygen to the cathode, is shown in the figure below. The grooved plates are made of a good conductor such as graphite or stainless steel.

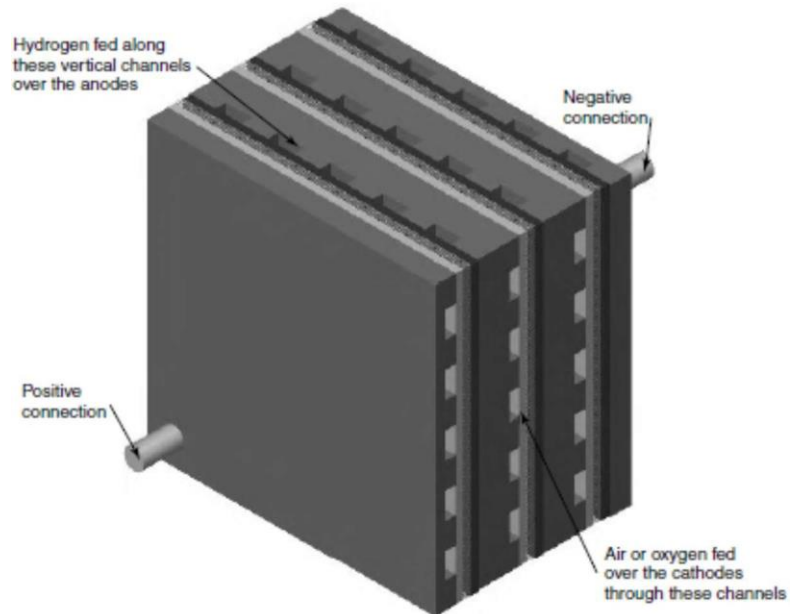


Simplified representation of a single fuel cell with connections for the power circuit and inputs for the supply of gases.

To connect multiple cells in series, they are **stacked** together. This stack has vertical channels for feeding hydrogen over the anodes and horizontal channels for feeding oxygen (or air) over the cathodes.

The result is a solid block that allows the electric current to flow efficiently, more or less straight through the cells, from one electrode to another.

As a result, the electrodes are well supported and the whole structure is strong and robust. The design of the bipolar plate is not simple. If the electrical contact is to be optimized, the contact surface should be as large as possible, but is unfavourable for the proper flow of gas over the electrodes.



A stack with 3 cells in which the bipolar plates form the connection between the cells.

Ideally, the bipolar plate should be as thin as possible, to minimize electrical resistance and to make the fuel cell stack small. The disadvantage is that the channels for the gas flow become narrow, making it more difficult to pump the gas around the cell.

In the case of low-temperature fuel cells, the circulating air must evaporate and the product must take away water. In addition, there are usually more channels through the bipolar plate for coolant.

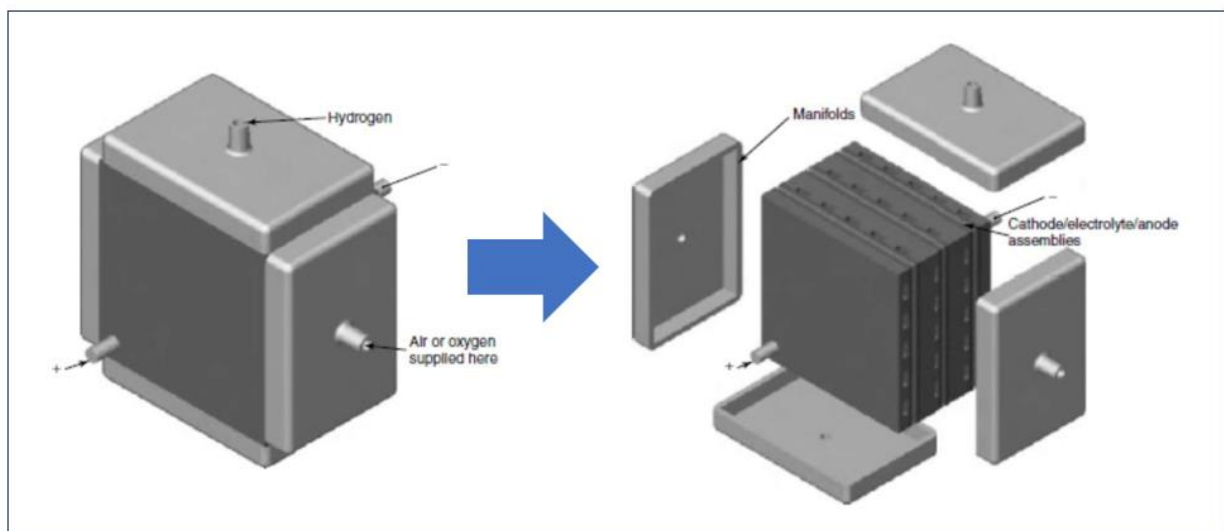
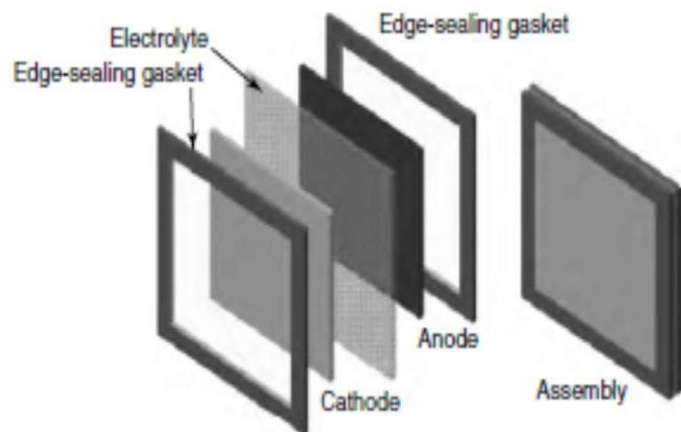


10.3 Gas Supply and Cooling

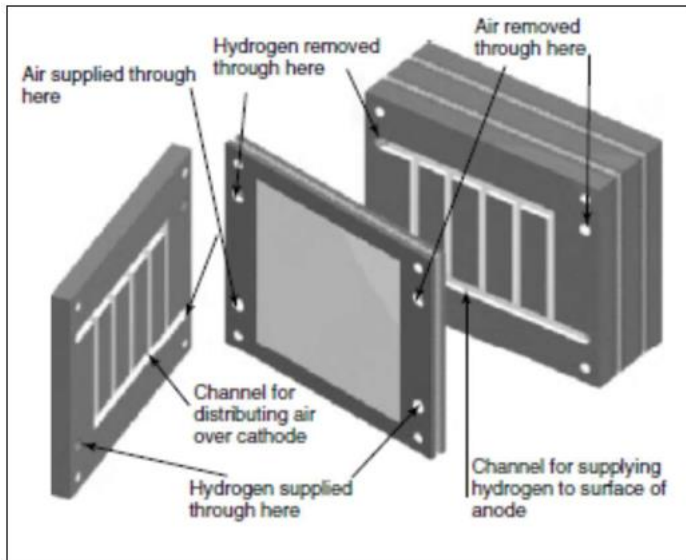
Theoretically, it is easy to develop a stack of multiple cells. However, there are problems with the gas supply and the prevention of leakage during the realization. Because the electrodes have to be porous, they would leak at the edges. As a result, the edges of the electrodes must be sealed.

Sometimes this is done by making the electrolyte slightly larger than the electrodes and fitting a sealing gasket around each electrode.

Such assemblies can be stacked where the hydrogen and oxygen can be delivered to the electrodes. Feeding systems and manifolds are used for this. Due to the connections around the edge of the electrodes, the hydrogen should only come into contact with the anodes as it is fed vertically by the fuel cell stack. Oxygen is fed horizontally by the stack and should only have contact with the cathodes.



A stack with 3 fuel cells, external manifolds and connection for the power. No cooling is possible in this setup.



The above simple setup is used in some systems, but it has some major drawbacks. The system is difficult to cool. Fuel cells are never 100% efficient, which generates large amounts of heat, energy and electrical energy.

In practice, this type of cell must be cooled by the air flowing over the cathodes. This means that more air must be supplied than necessary for the chemical reaction. Sometimes this is enough to cool the cell, but it remains a waste of energy.

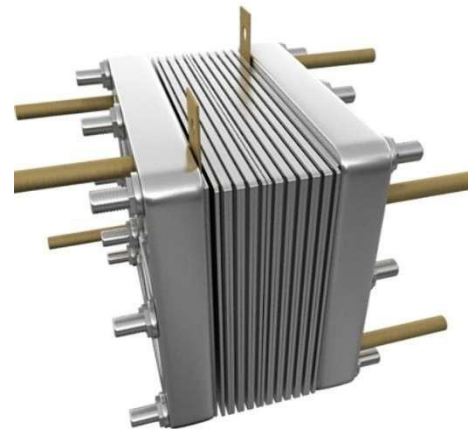
The second disadvantage is that the gasket around the edge of the electrodes is not pressed evenly (e.g. at the point where there is a channel). This results in an increased risk of leakage of the reaction gases.

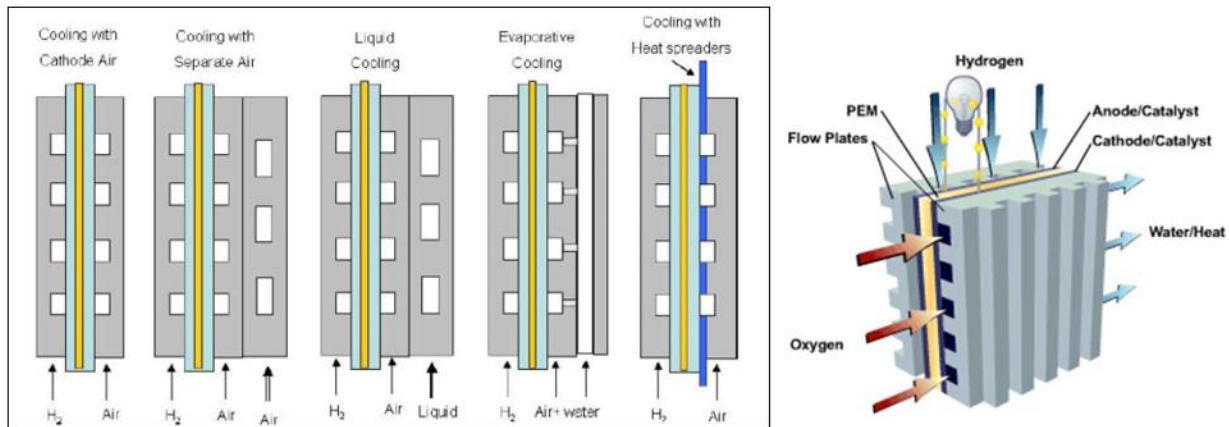
A solution requires a more complex bipolar plate. The plates are made larger in relation to the electrodes and have extra channels running through the stack that feed the fuel and oxygen to the electrodes.

Carefully placed holes feed the gases into the channels that run across the surface of the electrodes. This type of control is called an internal manifold. It results in a fuel cell stack as a solid and solid block with the reacted gases being fed inside at the ends. The end plate is quite complex, with different connections.

In addition, we see the typical shape of a fuel cell as a solid block of multiple cells with connections at each end.

The bipolar plate with internal manifold can be cooled in different ways. The easiest way is to use narrow vertical channels by running the plates and cooling air or water through them. Other possibilities are condensing air and/or using a heat conductor.





Schematic representation of the cooling methods in a PEM.

Obviously, the bipolar plate is usually a complex component in a fuel cell stack. The choice of material is also not easy. Graphite is often used, but it is difficult to work with because it is brittle. Stainless steel can also be used, but it will be able to lead to corrosion in some types of fuel cells.

Ceramic materials are used in very high temperature fuel cells. The bipolar plate therefore always makes up an important part of the cost of a fuel cell. The risk of leakage is relatively high when such a diversity of parts is assembled. The gas could escape along the porous edge of the electrodes. Other weak spots are the connections between each bipolar plate. In addition, the smallest hole in an electrolyte leads to serious follow-up leakage.

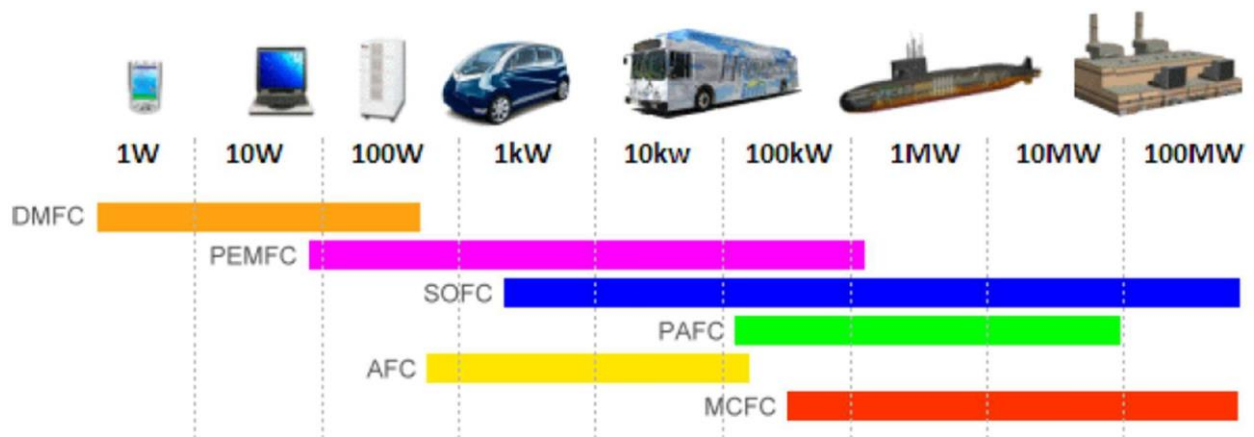
10.4 What types of fuel cells are there?

In addition to the cost, the **3 fundamental technical problems** with fuel cells are:

- High quality requirements for hydrogen.
- The low reaction speed at a fluctuating load.
- The availability of hydrogen.

To solve these problems, different types of fuel cells have been developed. The different types are usually distinguished by the electrolyte used, but there are always other important differences as well. We now distinguish different classes of fuel cells as viable systems for now and the near future. An overview can be seen in the table below (Source: WBZU, ZSW, CALLUX via Vives University of Applied Sciences).

	AFC	PEFC/PEM DMFC	PAFC	MCFC	SOFC
Designation	Alkaline FC	Polymer electrolyte / direct methanol FC	Phosphoric acid FC	molten carbonate FC	Solid oxide FC
Temperature	low	<100°C		up to 800°C	high
Catalyst Material	noble	Platinum		Metals	less noble
Gas Requirement	ultrapure	4-5.0 H ₂		C _n H _m	less pure
Cell Efficiency	low	40-50%		50-60%	high
System Complexity	high	Reformer		Internal Reformer	low
Start-Up-Time	low	Seconds		Hours	high
Dynamism	high				low



Overview of the fuel cells according to the power.

The proton-exchange membrane fuel cell (**PEMFC** = Proton Exchange Membrane Fuel Cell) benefits from the essential simplicity of the fuel cell. The electrolyte is a solid polymer in which protons are mobile. The chemistry is the same as the acid electrolyte fuel cell. The cells operate at fairly low temperatures, so the problem of slow reaction must be addressed by using advanced catalysts and electrodes. Platinum is the catalyst, but developments in recent years mean that only minute amounts need to be applied that can also be recycled well.

Platinum is therefore a small part of the total price of a PEM fuel cell. PEM fuel cells only work on very pure hydrogen and can become contaminated if traces of CO and CO₂ are present in the hydrogen. There are purification processes for this.

A theoretically very attractive solution for the hydrogen supply is the use of methanol as a fuel. This can be done in the PEM fuel cell and are called direct methanol fuel cells (**DMFC**) where the methanol will be used as fuel in liquid form. The disadvantage of these cells is the low reaction speed because an extra conversion is required.

Although PEM fuel cells were used on the first manned spacecraft, the alkaline fuel cell (**AFC**) was used on the Apollo and Shuttle Orbiter Craft. The problem of slow reaction speed has been overcome by using highly porous electrodes with a platinum catalyst and by operating at fairly high pressure.

The phosphoric acid Fuel Cell (**PAFC**) is the first type produced in commercial quantities. This principle is used in many 200kW systems and was manufactured by the International Fuel Cells Corporation. Porous electrodes, platinum catalysts, and a fairly high temperature (~220°C) are used to increase the reaction speed to a reasonable level. The problem of hydrogen refueling is solved by reforming natural gas (predominantly methane) into hydrogen and carbon dioxide. In addition to the cost, the big disadvantage is also the size of the fuel cell system. PAFC systems use the simplicity of a fuel cell to achieve an exceptionally reliable and maintenance-free energy supply. Several PAFC systems run continuously for long periods with low maintenance.



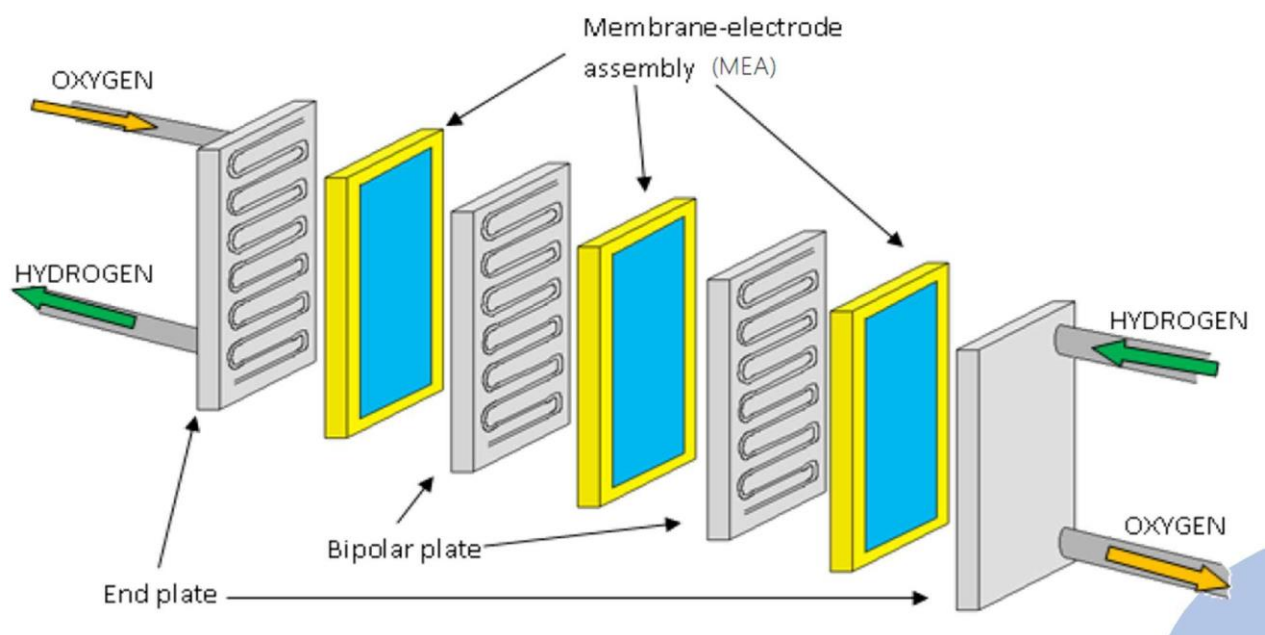
Each fuel cell type has advantages but also challenges. The Solid Oxide Fuel Cell (**SOFC**) operates in the temperature range of 600 to 1000°C. This means that high reaction rates can be achieved without expensive catalysts and gases such as natural gas can be used directly. It can also be reformed internally within the fuel cell without the need for a separate unit.

The expensive production costs of the ceramic materials in the cells are disadvantageous. In addition, a fairly large amount of additional equipment is needed to make a complete fuel cell system. This includes air and fuel preheating. The cooling system is also complicated and not easy to start.

Despite its operation at temperatures up to 1000°C , the SOFC always remains in its solid form. This is not the case with the Fused Carbonate Fuel Cell (**MCFC**), which has the interesting property of needing the carbon dioxide in the air to work. The high temperature means that a good reaction speed is achieved by using a relatively inexpensive nickel catalyst. The nickel also forms the electrical base of the electrode. Like the SOFC, the MCFC can use gases such as methane and syngas (H_2 and CO) directly without an internal reformer.



Take a look at the schematic representation of a fuel cell below. Which type do we see? Explain how it works in your own words. Additional information can be found on the internet.



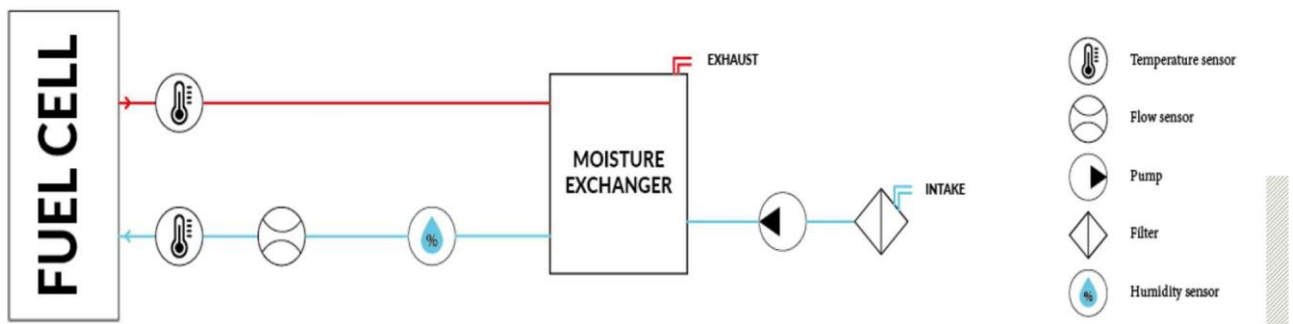
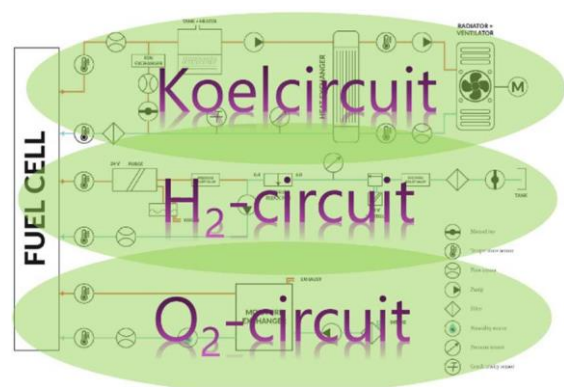
10.5 BOP: Balance of Plant

As we have seen, the nucleus of a fuel cell consists of electrodes, the electrolyte and the bipolar plate. In addition, there are additional components where one will speak of the **Balance of Plant** (= BOP).

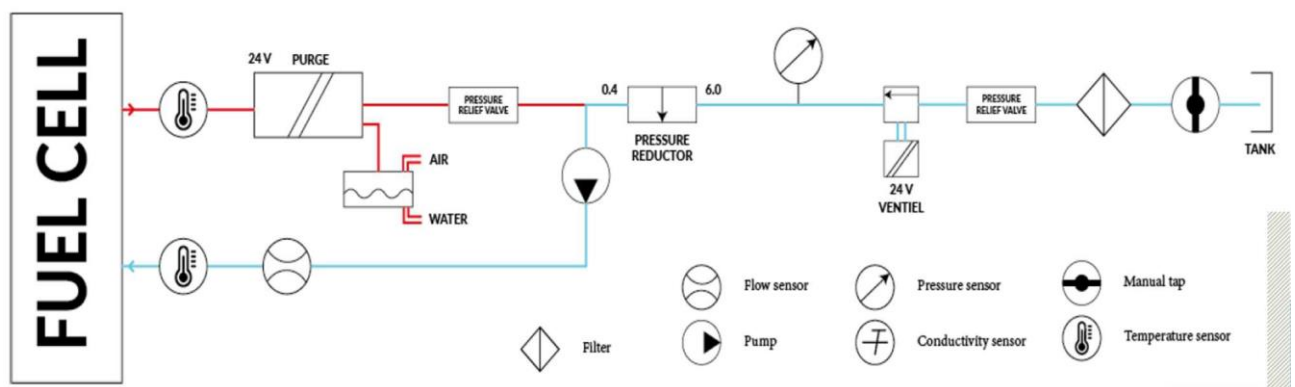
It is a term to refer to **all the additional supporting** components and auxiliary systems of a power plant. The generating unit itself is not part of this.

In the hydrogen industry, we usually talk about **3 circuits**:

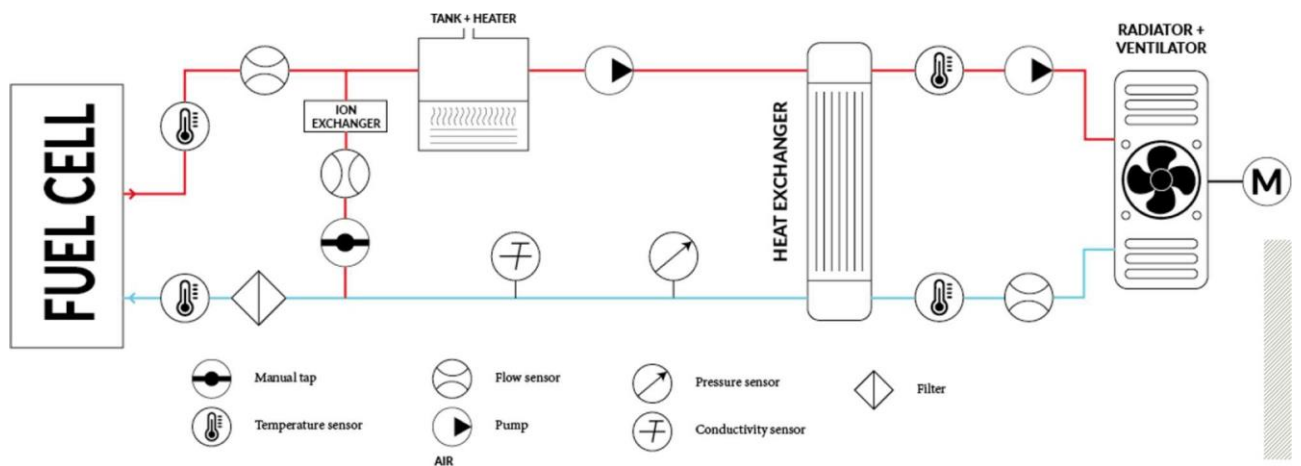
- oxygen (O₂)
- hydrogen (H₂)
- refrigeration.



Schematic overview of an oxygen circuit (source: VIVES University of Applied Sciences).



Schematic overview of a hydrogen circuit (source: VIVES University of Applied Sciences).



Schematic overview of a refrigeration circuit (source: VIVES University of Applied Sciences).

The additional components required depend very much on the nature of the fuel cell and the fuel used. On the following page, we see a brief summary of the most important parts that could also be found on the schematic representations of VIVES University of Applied Sciences:

Air and fuel supply: in all but the smallest fuel cells, the air and fuel will have to be distributed via the stack with pumps or blowers. Refrigerated compressors are often used.

Electrical power conversion: the direct current (DC) output of a fuel cell stack will rarely be suitable for direct connection to an electrical charge where a power regulator is necessary. This can be a voltage regulator or a DC/DC Converter. A direct current to alternating current converter (DC/AC) is expensive. Electric motors drive the pumps, blowers, and compressors and are a vital part of a fuel cell system.

Fuel storage, including the supply and storage of hydrogen.

Fuel reform: if the fuel cell does not use hydrogen, a fuel processing system will be needed.

Different control valves as well as pressure regulators will usually be needed. In most cases, a controller will be needed to coordinate the components of the system.

A cooling system will be needed for the larger fuel cells. In the case of a CHP, this will be a heat exchanger so that the heat is not lost but used in another process.

A humidifier has been added to humidify one or both gases. A slightly moist membrane is necessary for transporting ions.



Balance of Plant in the industry for large capacities up to 1000 MW.



BOP also small and compact? Compact fuel cell systems of a car. The power outputs are 150 kW ratio.

10.6 Future?

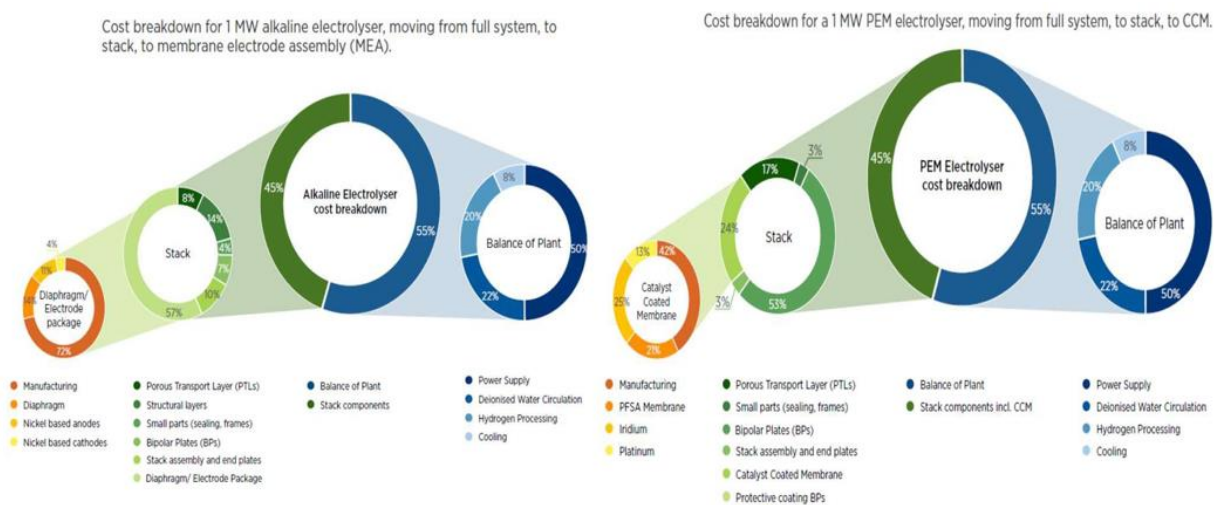
Fuel cells are **more efficient** than combustion engines and can also be used in small local systems to generate electricity.

Fuel cells are simple and compact with few or no moving parts. This will lead to reliable systems with a long service life. It even has a longer lifespan than batteries.

An additional advantage is the sound of the system. Fuel cells are very quiet! This is important in portable, mobile or stationary applications.

There is also talk of low emissions from pure water as a by-product, which is why we speak of **zero emission**.

Unfortunately, there are also disadvantages... For the time being, it is still a lesser-known technology, but the main disadvantage is the cost! The use of more expensive materials such as platinum and the small production are called a high **capex**. The overviews below prove this. Hopefully, production will increase in the coming years, which will reduce the cost price!



Comparison of costs between PEM and MEA technology (source AGFA).

11. HYDROGEN AS A FUEL?

Hydrogen is an **energy carrier** in which the energy can also be released by burning hydrogen. We have already seen that hydrogen is very explosive and highly flammable. With this data, we can burn hydrogen in a controlled manner. It can be a substitute for gaseous fuels (such as methane) and liquid fuels (petrol and diesel). The big advantage is that the combustion gases do not contain CO₂.

Another important advantage is that a conversion to hydrogen combustion can be achieved with relatively limited adjustments. Hydrogen can also be mixed with fossil fuels.

The disadvantage is twofold: the efficiency in the combustion engine is lower than the efficiency of a fuel cell.

In addition, NO_x is released due to the higher temperatures. These are nitrogen oxides in gaseous form that are mainly released during the combustion of fossil fuels such as vehicle exhaust fumes, industrial emissions,... This group of gases consists mainly of nitric oxide (NO) and nitrogen dioxide (NO₂).

For this reason, the automotive world or **automotive** is now opting for fuel cells. However, there are plenty of other possibilities, especially in heavy vehicles with large engines. This also brings the maritime world into the picture

because these engines can be converted to hydrogen fairly easily.

In the built environment, burning hydrogen is a useful alternative to natural gas. Because the existing network can be used for distribution, only the burners of central heating boilers need to be replaced. However, studies indicate that hydrogen is less efficient than heating with a heat pump.

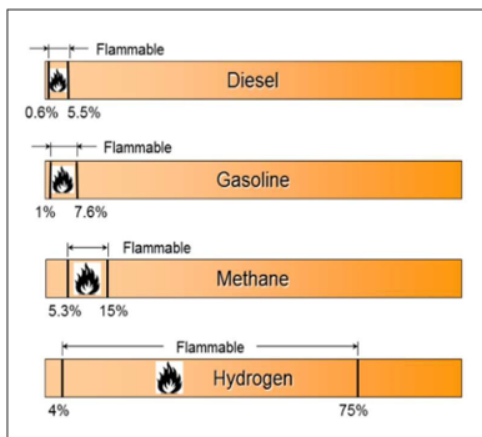
Finally, hydrogen is also interesting as a fuel in power plants.

11.1 Burning hydrogen

When we look at the various fuels, we notice that hydrogen is a highly flammable gas.

It has flammability limits of 4 to 75% vol% fuel in the air. The temperature in the hydrogen flame can reach more than 2000°C in an oxygen atmosphere, and the minimum ignition energy of 0.02 mJ is very low. It is therefore necessary to use burners that are specifically adapted for hydrogen.

In the meantime, central heating boilers have already been developed that run on 100% hydrogen so that they can also be used to heat homes and buildings. The problem in residential construction is currently the supply of hydrogen. Producers for central heating boilers are currently developing devices that can easily be switched to hydrogen as a fuel in the future.



	Hydrogen	Gasoline Vapor	Natural Gas
Flammability limits	4 – 75%	1.4 – 7.6%	5.3 – 15%
Explosion limits	18.3 – 59.0%	1.1 – 3.3%	5.7 – 14%
Ignition energy	0.02 mJ	0.20 mJ	0.29 mJ
Flame temperature	2045°C	2197°C	1875°C

Combustion properties of fuels.

11.2 The combustion engine

The principle of a hydrogen combustion engine is based on a **mixture engine** in which the fuel mixture is ignited by means of a **spark plug**. It is also called an Otto engine and was developed in the 19th century by the family of the same name.

The combustible mixture of fuel and air is formed outside the combustion chamber in a so-called carburetor or by fuel injection into the intake manifold and nowadays also directly into the cylinder. Under normal conditions, air contains 80% nitrogen (N₂) and 20% oxygen (O₂).

Due to the oxygen present, this mixture is flammable in the correct mixing ratio. In the combustion chamber, the mixture is sucked in by a negative pressure that is created there during the intake stroke.



After the intake stroke, the compression stroke follows: the mixture is compressed. After this, a spark ignites the mixture. This causes an increase in pressure which leads to an increase in volume. This increase in volume creates so-called labor stroke. An effort is made that makes a vehicle start operating.



Curious about the simplified operation of a four-cylinder in a diesel engine? Follow the link.

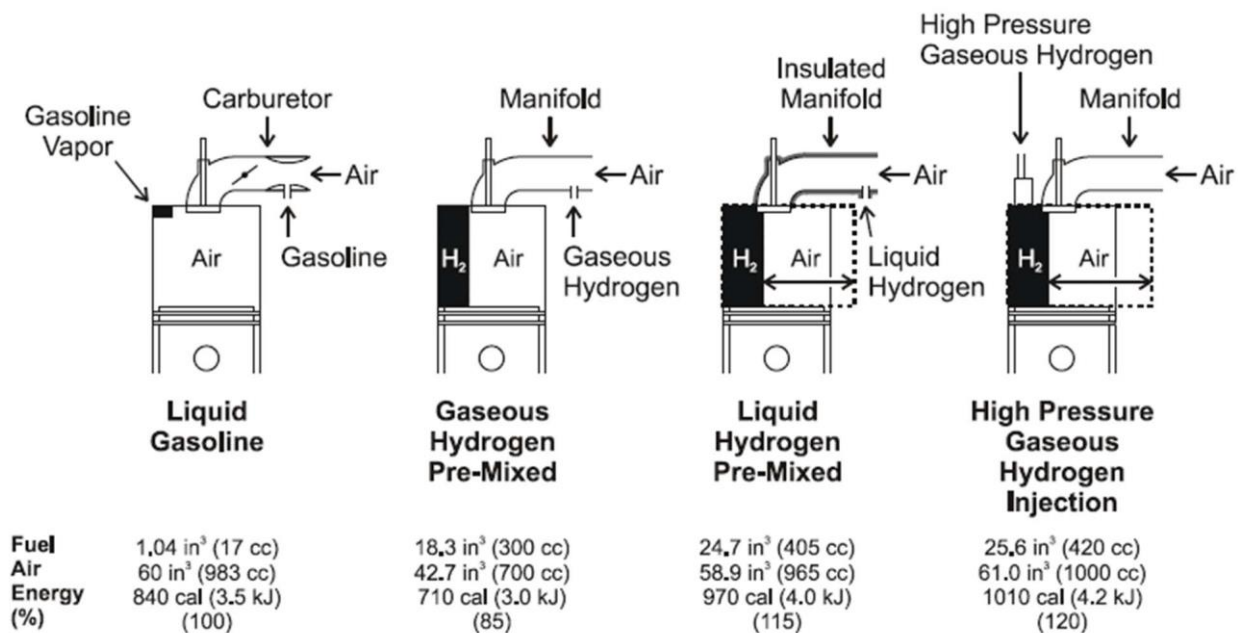


The idea of integrating hydrogen dates back to around 1930. Hydrogen can be mixed with another fuel or used as a pure fuel. The important improvement is that hydrogen admixture can increase the efficiency of the engines.

If only hydrogen is used as a fuel, there are **three different options** to achieve this:

- Mixing hydrogen gas with air in the intake manifold.
- Inject liquid hydrogen into the intake manifold.
- Injecting liquid hydrogen into the combustion chamber.

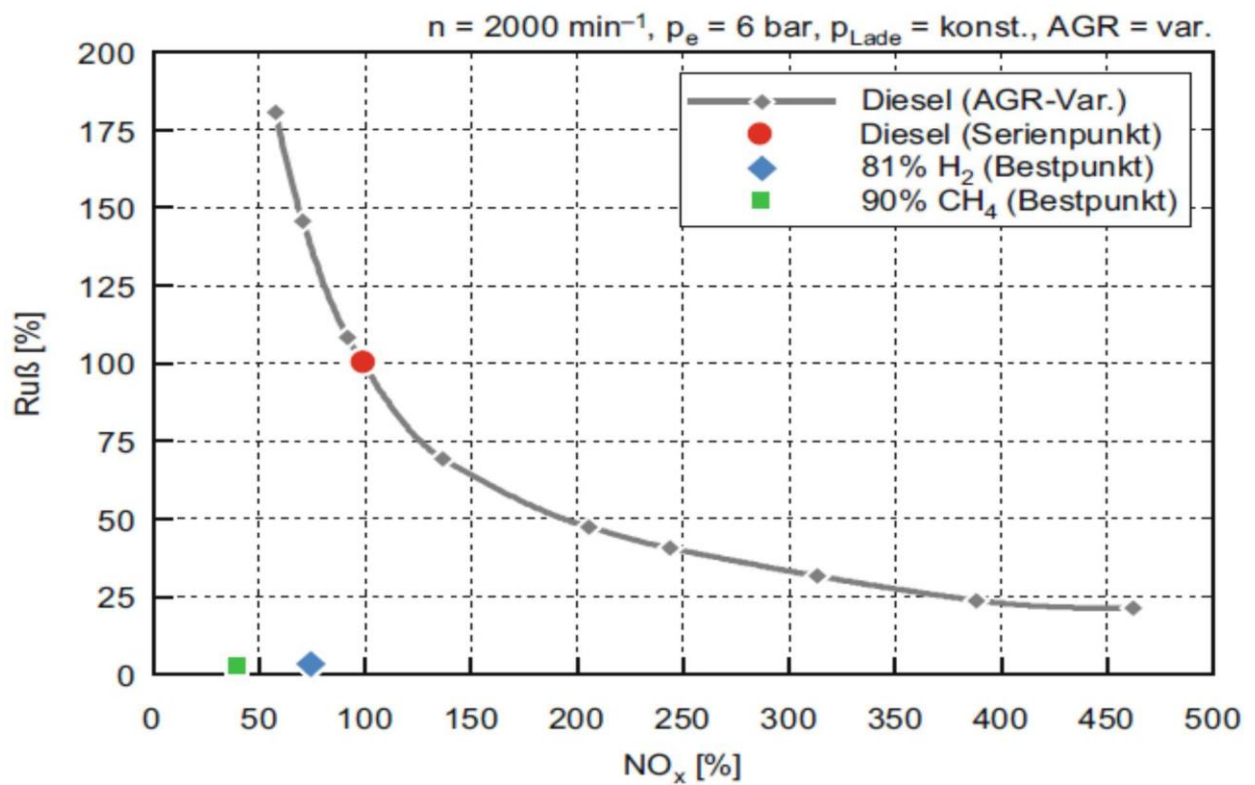
The option depends on how the state of the hydrogen is: gas or liquid. Cryogenic storage is necessary for liquid hydrogen. With hydrogen gas, the power is about 15% lower than with the petrol engine with the same capacity. With other options, the specific power is respectively 15% and 20% higher than with the petrol engine.



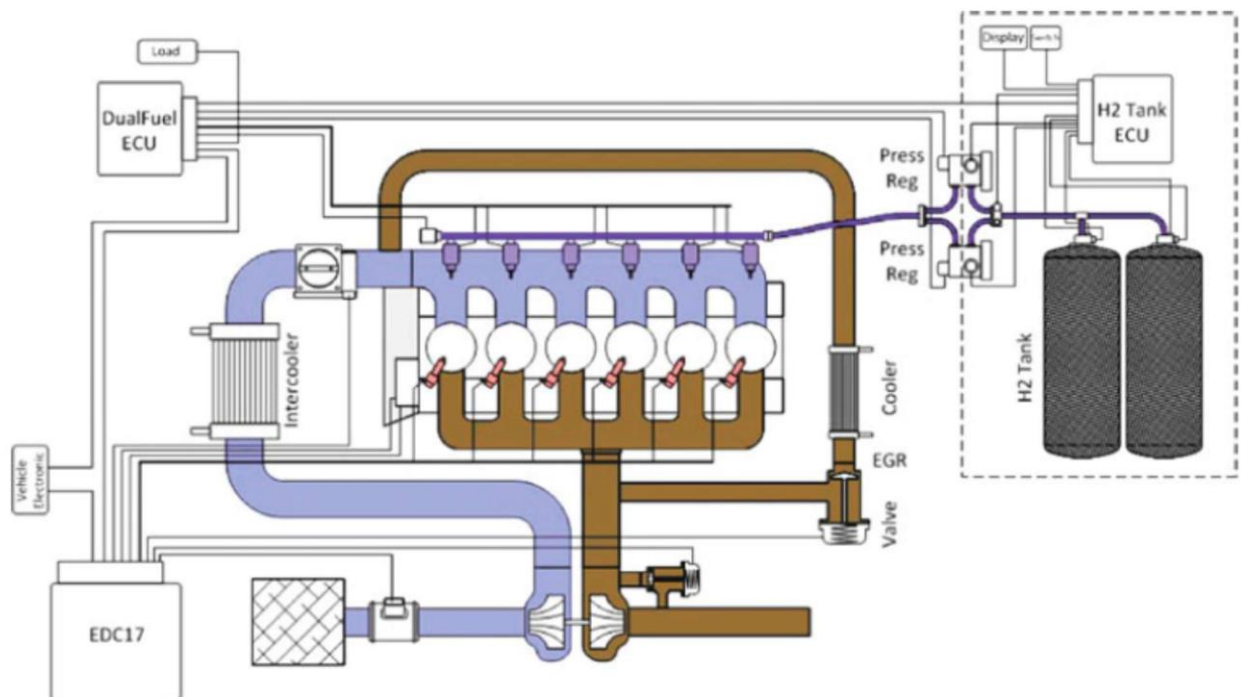
Principles of a hydrogen combustion engine.

Several concepts have been developed, both based on diesel and mixture engines. For diesel engines, natural gas and hydrogen gas can be chosen as alternatives. In both cases, a strong reduction in soot emissions is achieved.

The graph shows the relationship between soot emissions and NOx. The higher the temperature, the lower the soot emissions and the higher the NOx emissions. By using hydrogen and natural gas, soot emissions become negligible, but NOx emissions still remain. This NOx can be converted back by means of a catalyst.



Relationship between the emissions of soot and NO_x from a diesel, natural gas (90% CH₄) and hydrogen gas (81% H₂) engine



Construction of a hydrogen – diesel dual fuel engine.

The **performance** of an engine in hydrogen or petrol mode can be compared with the table below. Remarkably, although the performance is the same in terms of power, that of hydrogen clearly lags behind the range of the vehicle. This is also the bottleneck.

	hydrogen	petrol
Max. power at engine speed	191 kW / 5100 rpm	191 kW / 5100 rpm
Max. torque at engine speed	390 Nm / 4300 rpm	390 Nm / 4300 rpm
Acceleration, 0-100 km/h	9.5 s	9.5 s
Top speed $v_{\max}$	230 km/h	230 km/h
Usable hydrogen storage capacity	7.8 kg LH ₂	74 litre
Overall consumption	3.6 kg/100 km	13,9 l/100km
Operating range	> 200 km	> 500 km
CO ₂ emissions	5 g/km*	332 g/km
Other emissions	<< EU4 limits	< EU4 limits

In addition, the combination with electric drive and a battery offers many more possibilities to achieve even better efficiency along the entire energy chain. In fact, the far-reaching development of electric propulsion and the subsequent development of fuel cells (cheaper and more compact) is the reason that combustion engines with hydrogen are in fact less interesting in large-scale production. A disadvantage with combustion engines is the noise production and of course the NO_x production (for which a catalytic converter must be used).

However, there are still possibilities when existing vehicles in particular need to be made more sustainable. There are special conversion kits for trucks and there are also applications in shipping. Where the lifespan of the vehicle or vessel is long, it is also worthwhile to convert it to hydrogen in combination with a combustion engine.

MAN Engines, MAN's engine division, has developed a new plan in cooperation with CMB. TECH converted a V12 diesel marine engine to a hybrid power source that can run on both hydrogen and diesel. Is this also something for the truck sector?

MAN converted a MAN D2862 LE428 into a D2862 LE448 for use on the Hydrocat 48, a vessel for personnel transport. The engine has 1029 hp at 2100 rpm. The conversion only consisted of retrofitting the hydrogen injection system.

MAN Engines has recently put its first two dual-fuel hydrogen engines for workboats into series operation. The engines are IMO Tier III certified and equipped with an exhaust gas after-treatment system with Selective Catalytic Reduction. Both V12 engines have been prepared for dual-fuel operation by MAN Engines and by development partner CMB. TECH from Antwerp supplemented with a hydrogen injection system. The low-emission engine is used on the world's first hydrogen-powered crew transfer vessel (CTV), the Hydrocat 48 from Windcat Workboats.

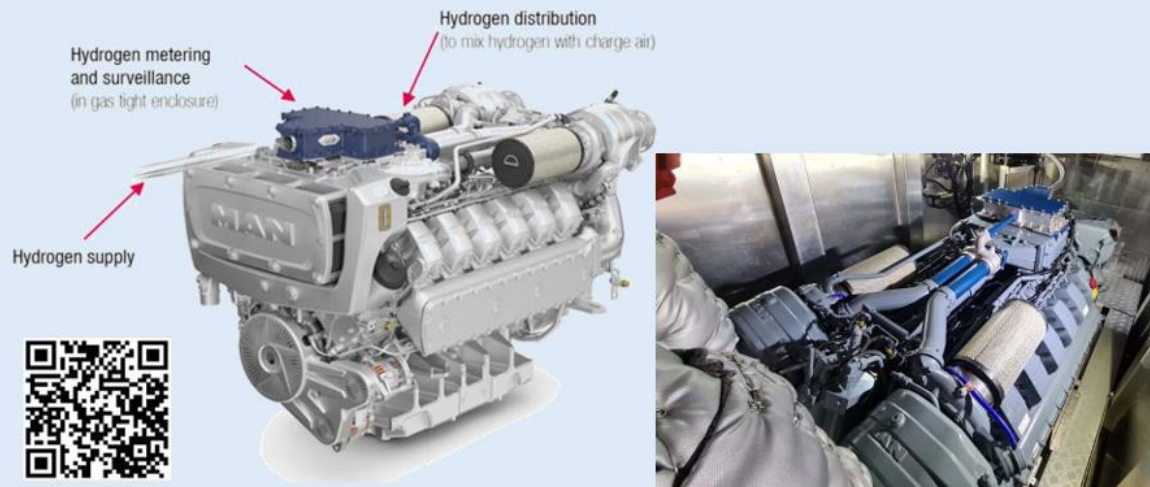
"The special thing about our technology is that we use a conventional diesel engine, which does not need to be optimised for hydrogen," says Werner Kübler, Head of Development at MAN Engines. A proven V12 marine engine is therefore used, in which hydrogen is introduced into the charging air via an adapter and added to the combustion cycle. The combustion process is initiated according to the diesel principle, which requires the injection of about 5 percent diesel fuel. Diesel parameters Common rail injections are optimized for dual fuel operation.

MAN Engines has many years of experience in the development of fuel-saving and reliable diesel engines, also for work vessels. Building on this experience, we have succeeded in achieving the best consumption values even in dual fuel operation and in the same operating behaviour as in diesel operation at full load.

At the same time, we are also reducing CO₂ emissions by an average of around 50% through the use of hydrogen, and even up to 80% as a peak value," adds Kübler.



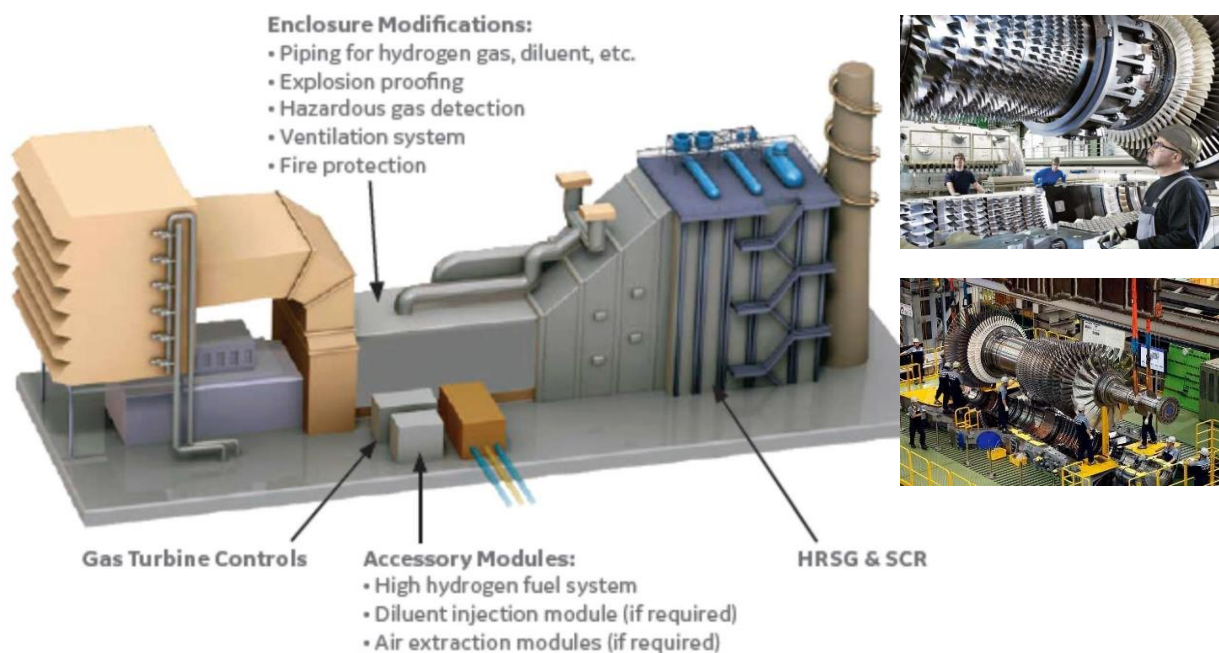
Another advantage of using the conventional and advanced diesel engine is the usual ease of operation in terms of maintenance and service. In addition, pure diesel operation can continue without interruption if, for example, the hydrogen supply is exhausted. Availability, driving comfort and operational safety are therefore always guaranteed at the high level that a traditional diesel engine is known for.



MAN Engines offers its customers and partners solutions such as the "MAN Smart HYBRID Experience" hybrid system or engines for gas/electric propulsion, in order to contribute to CO2 reduction and sustainable shipping. Now that the MAN D2862 LE448 dual fuel engines for workboats are ready for series production, a new milestone has been reached in this respect. "By starting with dual fuel combustion engines, we can make hydrogen technology operational in the industry and kick-start the further development of the technology, regulations, supply chain, etc.," says Willem van der Wel, Managing Director of Windcat Workboats. Source: MAN engines

11.3 The hydrogen turbine

Gas turbines are also used in power plants. Hydrogen gas will also be available as a fuel. The existing installations must be adapted to guarantee safety. One of the most important points of attention is the combustion temperature. The greater the proportion of hydrogen in the fuel, the greater the modifications to the system. Below, you see a composition of a gas turbine with hydrogen:

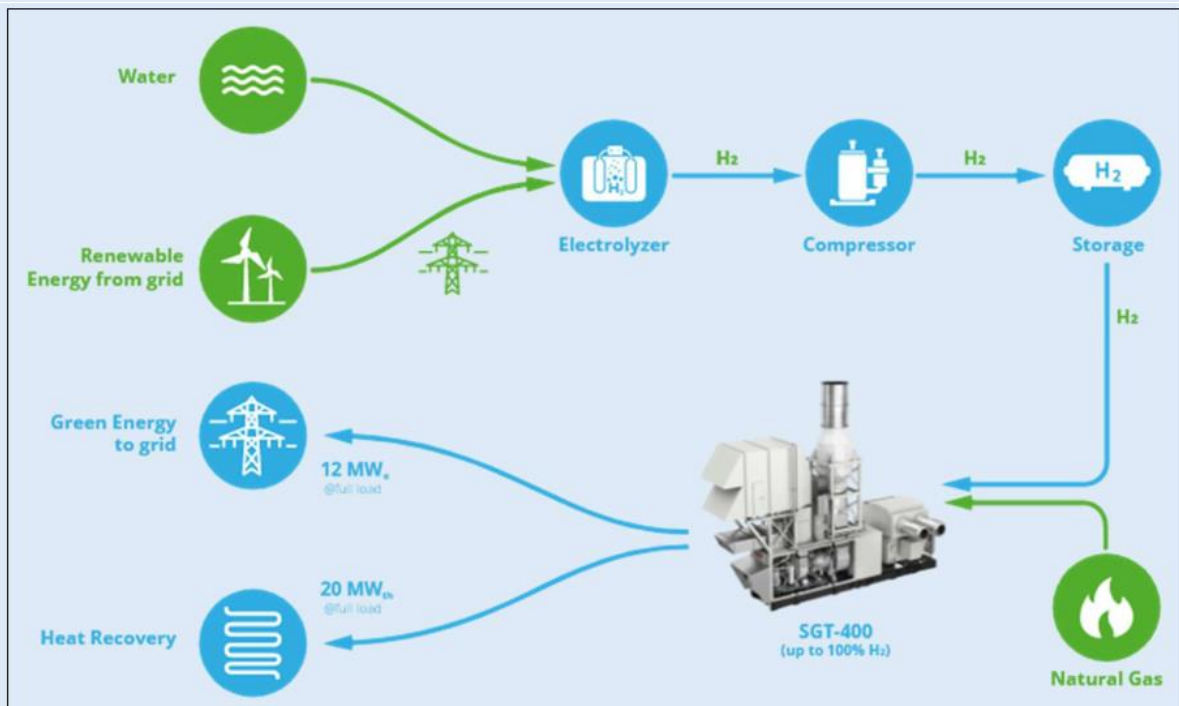


The HYFLEXPOWER project has commissioned a full hydrogen system at the factory site of Smurfit Kappa, the world leader in paper packaging, in Saillat-sur-Vienne (France). The project consists of producing, storing and using the 100 percent renewable hydrogen. The hydrogen is used to power a Siemens Energy SGT-400 industrial gas turbine.

Construction of the industrial gas turbine started in 2021. The turbine was able to start a first series of tests in 2022. In this phase, a mixture of natural gas with 30 percent hydrogen was used. Last week, the power-to-hydrogen-to-power demonstrator proved that state-of-the-art turbines with dry low-emission technology can be fed with up to 100% hydrogen, as well as natural gas and any mixtures in between.



The required hydrogen is produced on site by a 1MW electrolyser and then stored in a tank of almost a ton. A Siemens Energy SGT-400 industrial gas turbine is then powered with the local hydrogen.



"The knowledge and experience we have gained from the HYFLEXPOWER project where we installed the 1st gas turbine to run on 100 percent hydrogen will help us to further develop our entire gas turbine fleet for a hydrogen-based future. The interaction between electrolysis, storage and hydrogen conversion at one site has been impressively demonstrated and now it is a matter of scaling up the results," says Karim Amin, Member of the Board of Management of Siemens Energy.

The HYFLEXPOWER project shows that hydrogen can be used as a flexible energy storage medium and that it is also possible to convert an existing gas-fired electricity turbine to renewable hydrogen. It is a real driver for accelerating the decarbonisation of the most energy-intensive industries.

Source: Siemens Energy



More information about the HYFLEXPOWER project of Siemens?
Follow the link.



12. WHAT IS AUTOMOTIVE?

Automotive is a collective term for companies that are active in the production and sale of vehicles and in particular automobiles. The maintenance of a car is not included. The word **automotive** is a compound of the Greek word autos (self) and the Latin word motivus (movement).

When talking about hydrogen technology in Automotive, there are **2 variants**:

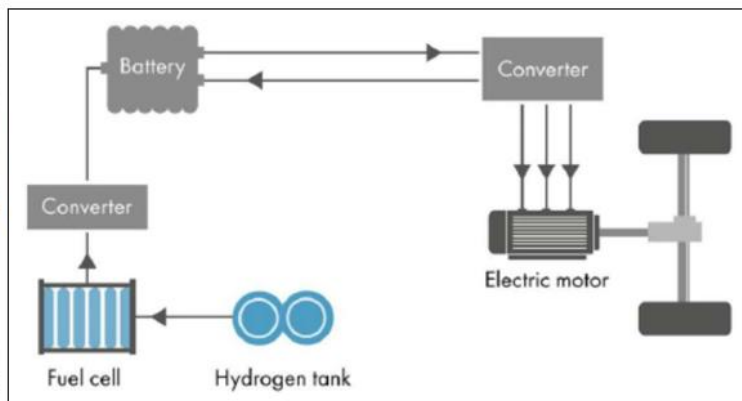
- A battery electric vehicle with a **range extender** or a range extender.
- A vehicle with only propulsion from the fuel cell.

The Mercedes Benz GLC F-cell of the first variant was launched on the market a few years ago. The new model has a unique plug-in hybrid setup that will combine the fuel cell and battery technologies. As a result, this model runs on both electricity and hydrogen. In hybrid mode, this SUV can drive up to 478 km with a full tank of 4.4 kg of hydrogen. In full electric mode, you can drive up to 51 km.

An advantage of this variant is that the advantage of pure electric driving applies to shorter journeys, which gives you a high efficiency. The battery delivers the maximum power and the fuel cell can be optimized for recharging the battery and can therefore become smaller and cheaper. A smaller fuel cell means that the power required for high-speed driving is limited.



Mercedes Benz GLC F – cell

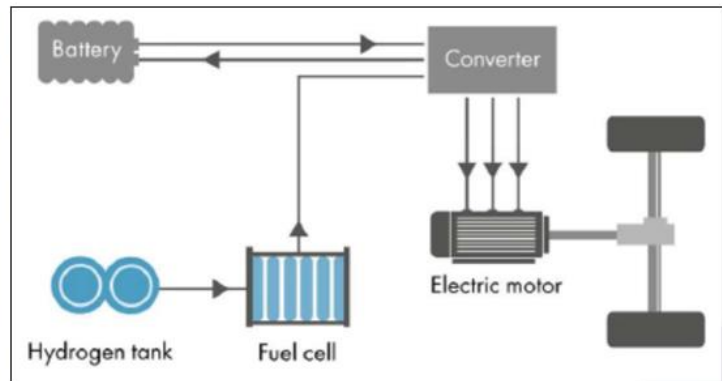


Schematic representation of electric vehicle with fuel cell range

An example of the second variant is the Toyota Mirai. In this vehicle, all the electrical power is provided by the fuel cell. This means a smaller battery but also a larger fuel cell. The Toyota Mirai has a battery with a maximum power of 9 kW.



Toyota Mirai



Schematic representation of fuel electric vehicle with battery as a buffer

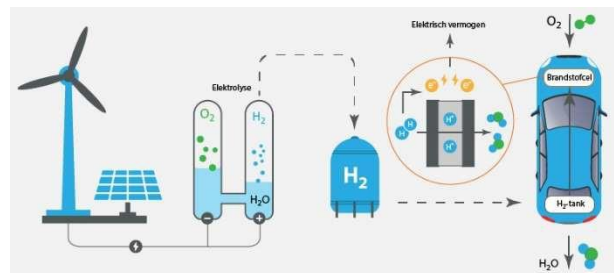
12.1 Why drive a car on hydrogen?

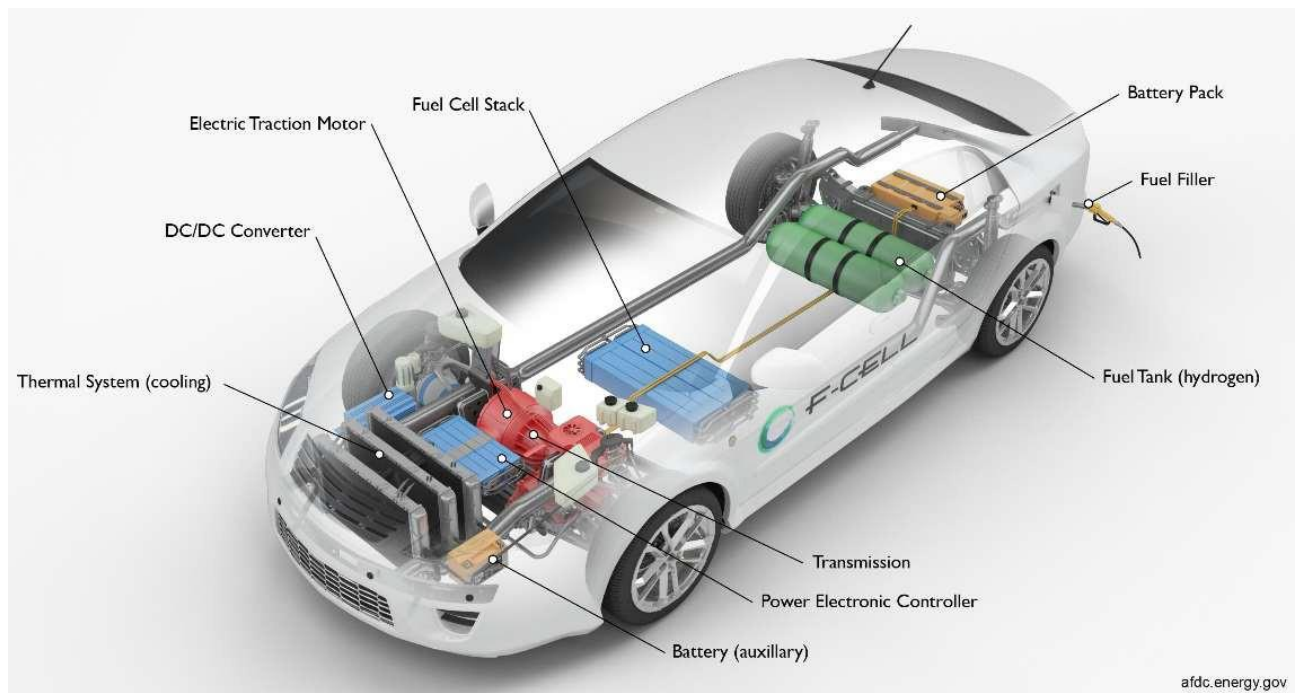
Electric cars are becoming increasingly popular and it is expected that all cars will run on alternative fuel in the future. Various manufacturers are therefore bringing new models to the market. That range now also includes the hydrogen car category. Could the hydrogen car be the future, or are there hidden defects?

A hydrogen car is a fully electric car. This four-wheeler is powered by one or even more electric motors. With this electric motor, electrical energy is converted into mechanical energy. With this mechanical energy, it is possible to power a tool or vehicle. The big difference between a regular electric car and a hydrogen-powered car is the way in which the energy that has been generated is stored.

In 2013, Hyundai brought the first hydrogen-powered car to the commercial market. Before you consider purchasing a hydrogen car, it is important to be aware of the limitations and benefits of the different models.

In addition to the cost, the range with a full tank is also important.





Construction of a hydrogen-powered car.



Hyundai Nexo



Toyota Mirai with installation of the hydrogen tanks.





Two commercial models include the Hyundai NEXO and the Toyota Mirai. Look for the specifications of these models and make a comparison such as the consumption, cost...

Hyundai NEXO	Toyota <u>Mirai</u>

In the genre of cars running on fuel other than fossil fuels, hydrogen is only a small category. Whether hydrogen will really break through remains to be seen.

The tank of a car that runs on hydrogen holds about 5 to 6 kilograms. A full tank costs about 50 to 60 euros. This allows you to drive a distance of an average of 500 kilometres, the price per kilometre of fuel is close to diesel. The purchase price of the hydrogen car is higher because there is currently a small production.

Although hydrogen cars, like battery electric cars, do not emit harmful substances while driving, generating the fuel hydrogen can have a harmful environmental impact. The advantage is that a hydrogen-powered car can be refuelled in just a few minutes. In addition, the range of the hydrogen car is considerably higher than a petrol car or battery electric car. Range refers to the number of kilometres you can drive on one fully fuelled battery.

The big difference between a hydrogen car and a regular electric car is the way of storing energy. The electric car uses a large battery pack. The hydrogen car, on the other hand, gets its energy from hydrogen.

If a hydrogen car starts producing hydrogen, about 50 percent of the energy is lost. There is talk of an efficiency of 30% when we look at the advantages of driving on hydrogen. With an electric car, this efficiency is no less than 95%.

The hydrogen future? At the moment, the hydrogen car is still under development. Only Toyota and Hyundai have released a model and because there are still few hydrogen cars on the road, there is no second-hand market yet.

Buying a hydrogen-powered car is therefore expensive. Not only the purchase price, but also the refuelling of hydrogen costs 1.5 to 2 times as much as charging an electric car. Hydrogen may not be a fossil fuel, but it remains an expensive fuel. Generating electricity, on the other hand, can be even cheaper if the consumer has solar panels at home.

As a result, electricity will not rise quickly in price and electric charging will remain cheaper than hydrogen filling up in the short term. In addition, the parts in a hydrogen car require more maintenance, which means that the maintenance costs of a hydrogen car are also higher.

So is buying a hydrogen car the future? At the moment, the electric car is the most popular choice among electric vehicles. However, we live in a time where technology plays a huge role and is making rapid progress.

12.2 Hydrogen refuelling in Belgium

Unlike an electric car, you fill a hydrogen-powered car the old-fashioned way, simply by refuelling. Refuelling a hydrogen-powered car takes about the same time as refuelling a petrol car and is therefore a lot faster than charging a battery from a battery – electric car.

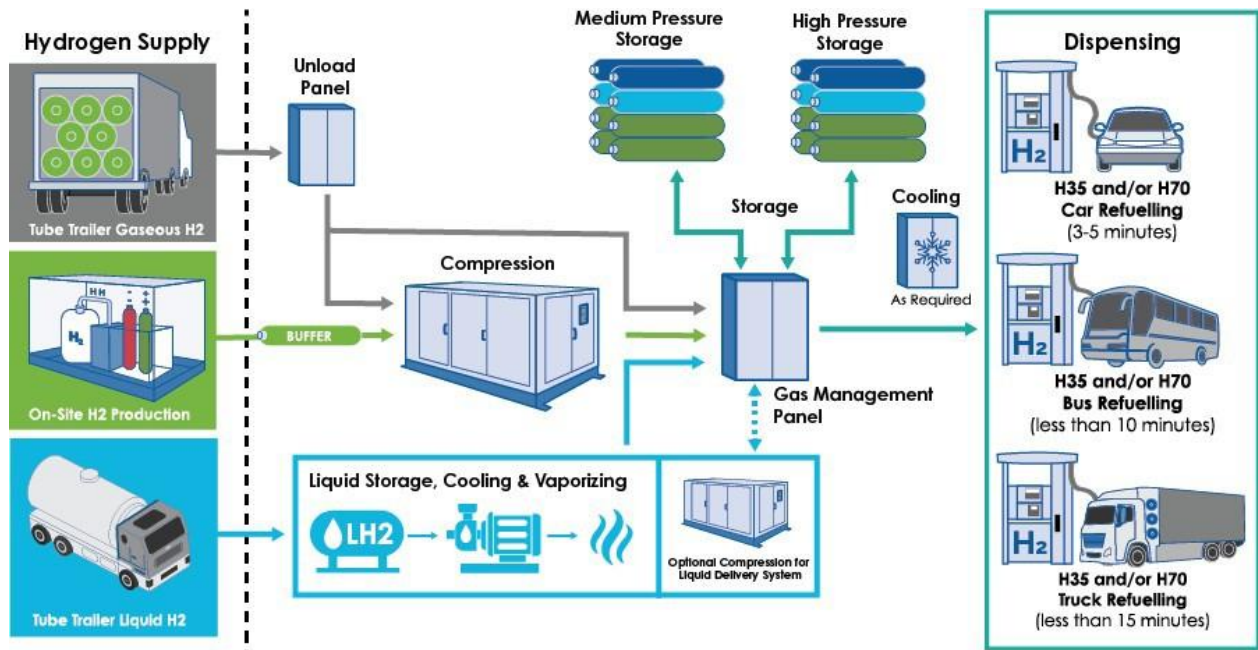
However, the fuel does not only come with advantages. There are currently few places where you can fill up with a hydrogen car in Belgium or the Netherlands. Partly because of this, the number of hydrogen-powered cars is still quite limited and You have to plan well to avoid ending up on the side of the road with an empty tank on a long journey!



As part of the H2Benelux project, WaterstofNet has drawn up the map below showing the status of hydrogen filling stations in the Benelux.



The international name for a hydrogen refuelling station is **Hydrogen Refuelling Station** or **HRS**. There is not much difference between a traditional diesel and petrol filling station and an HRS: you drive to the pump, connect the nozzle to the vehicle and start the refuelling process. However, some processes in the background are slightly different at a hydrogen filling station.



Schematic representation of a hydrogen refuelling station or HRS.

It starts with the supply of the alternative energy carrier. Hydrogen is usually also transported to the filling station by truck. There are also exceptions where hydrogen is produced on the site itself. Because of the explosive atmosphere the fuel is stored in a **pressurized tank**.

The biggest technical challenge of a hydrogen filling station lies in the refuelling process. In the low-pressure tank in which the hydrogen is stored, the hydrogen has a pressure of 20 to 200 bar. When refuelling, this pressure must be increased many times depending on the vehicle. This is done in **the high-pressure compressor**.

Once the hydrogen has been compressed to the correct pressure, it can be refuelled at the pump with a **nozzle**. To ensure that refuelling is safe and that no hydrogen leaks out, magnetic field sensors check that the nozzle is properly seated on the vehicle's tank. These sensors also detect any vibrations (= unforeseen collision,...) and can immediately stop the refuelling process in case of emergency.



Take a look at the setup of an HRS with different components below. Place the correct English name with the various components.



	Cooling system
	Air heater
	Container with compressor
	Aluminium block with the H ₂ heat exchanger

	Dispenser with nozzle.
	Hydrogen Supply
	Middle and high pressure H ₂ tanks



Some processes create high temperatures and people start using chillers. Where will these components be fitted into a hydrogen filling station?
What is the purpose of this component?

12.3 Hydrogen-powered buses

Buses are one of the most important forms of transport in Belgium. Every day, more than 1 million people use public transport to go to school, work or other destinations. The bus is therefore a popular choice because it allows you to travel from A to B relatively easily and cheaply. Because people are environmentally conscious, they are looking at greener alternatives such as the hydrogen bus.



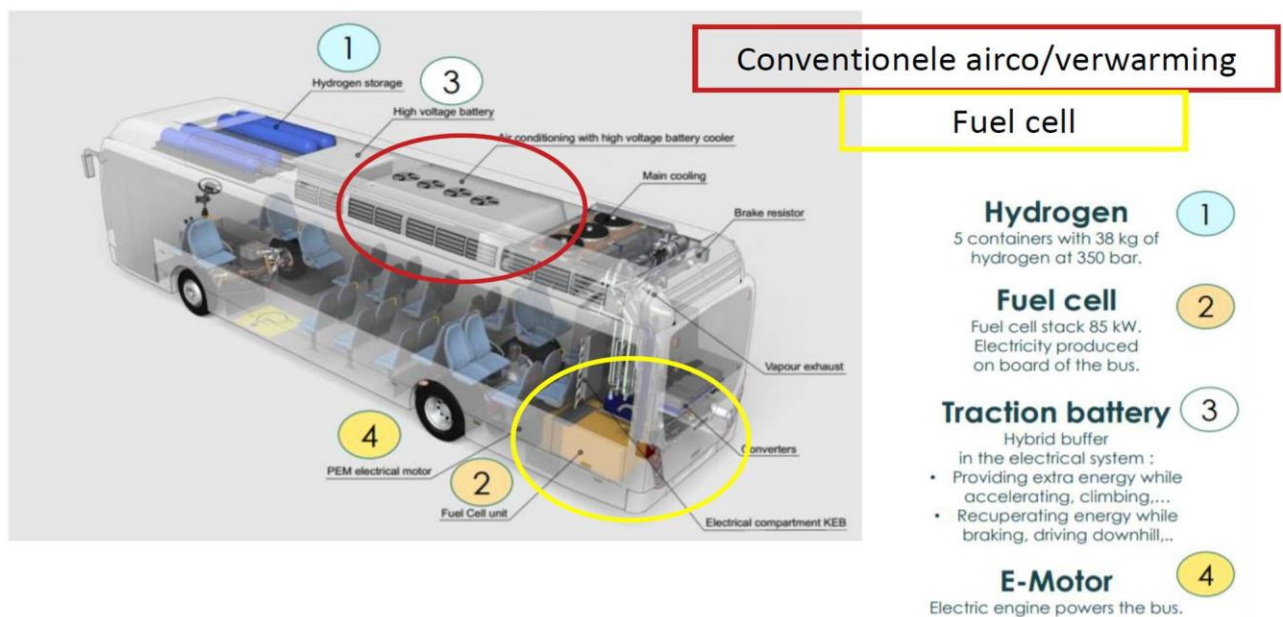
The hydrogen gas is stored in the tank of the bus, which is measured in kilos instead of litres. Most hydrogen buses have a tank of around 25 kilos, with which one can drive about 300 kilometres continuously. In addition, every hydrogen bus contains a fuel cell (or hydrogen combustion engine) which converts the hydrogen gas into electricity. So in addition to a hydrogen tank, every hydrogen bus also has a battery.

The big disadvantage of driving with batteries is the weight. In an electric car, this is not a big problem yet since these vehicles are not that heavy, but it is a problem when you want to drive an electric bus or even truck. These vehicles need so many batteries to drive far that they become too heavy, so that each battery has to use a lot of electricity to move forward.

With buses, too, one has to make a choice to reduce the weight: fewer batteries or fewer passengers. Both solutions are not optimal: fewer batteries = less distance traveling. Fewer passengers is certainly not a solution? For these reasons, buses that run on hydrogen are being considered.

A hydrogen bus can drive more than 300 kilometres with one refuelling of about 10 minutes. Electric buses often have to charge for hours to drive 150 kilometres. This is logistically annoying: bus is stationary and passengers have to wait. In addition, the batteries of electric buses also last less long in winter, which is not the case with hydrogen buses.

Hydrogen buses cost more than 600,000 euros when purchased. When you compare this to diesel buses of 225,000 euros and electric buses of 450,000 euros, this is a considerable amount. This is partly because the fuel cell of a hydrogen bus already costs more than 130,000 euros. This is also almost exactly the difference between the cost of an electric bus and hydrogen bus. Furthermore, the buses are very similar.



Construction of a hydrogen bus

The costs for hydrogen refuelling are still fairly high. Filling up with one kilo of hydrogen currently costs about 12.10 euros including VAT. A full tank therefore costs about 250 euros on which a hydrogen bus can drive 300 kilometres. Converted, this is 83 cents per kilometre. For an electric bus, it is about 10 cents per kilometre. This means that a hydrogen bus is now 8x more expensive to use than the electric alternative.

A diesel-powered city bus travels about 3 kilometres per Liter of diesel. A Liter of diesel currently costs about 1.90 euros. If we convert this to a journey of 300 kilometres, a diesel bus costs about 0.63 cents per kilometre. An electric bus is therefore also a lot cheaper than a diesel bus in terms of cost per kilometre.

The maintenance costs between electric and hydrogen buses are almost identical. The fuel cell of the hydrogen bus lasts about 1 million kilometres, which amounts to about 130,000 euros in maintenance costs. If we compare this with diesel and electric buses, we arrive at the following:

	Bus on diesel	Electric bus	Hydrogen bus
Maintenance costs per kilometre in euro	0.20 euros	0.10 euros	0.13 euros

We notice that the maintenance costs are comparable to an electric bus. If we also add purchase price and refuelling costs, we can conclude that an electric bus is still cheaper than a hydrogen bus.

In short, there are advantages but also disadvantages.

Advantages of hydrogen-powered buses:

- As mentioned earlier, refuelling hydrogen is a lot **faster** than charging an electric bus. Refuelling takes about 10 minutes compared to several hours. In addition, hydrogen buses can travel about **double** the distance.
- Buses that run on **green hydrogen** do not emit CO₂, making a hydrogen bus a better alternative than diesel buses with regard to the environment.
- A hydrogen bus has about the same properties as an electric bus. As a result, there will be no noise or odour nuisance, which is mainly positive in the cities .
- Because hydrogen buses are a lot **lighter** than electric buses, they will put less strain on the roads than electric buses. In addition, this allows you to drive a lot longer on one tank compared to the energy you need for all the batteries in an electric bus.
- Technologies have developed to such an extent that hydrogen gas **is safely** stored in special tanks.

Disadvantages of hydrogen-powered buses:

- Since hydrogen buses are very expensive to purchase, these buses are heavily **subsidized** by the EU. Because developments in this industry are very dependent on this, there is a high risk that it will stagnate when the subsidies stop.
- Buses that run on hydrogen are more expensive than electric buses both in purchase and per kilometre . Electric buses cost 10 cents per kilometre, while hydrogen buses cost 83 cents per kilometre.
- Currently, 95% of all hydrogen gas is generated using natural gas, which means that **CO₂** still ends up in the atmosphere. Only if we switch to green hydrogen does it make environmental sense to use hydrogen buses instead of diesel buses.
- One of the sore points of electric buses is **the range**, which is currently still too small. But of course this development does not stand still either, it could just be that this will be solved within a few years and therefore one of the main advantages of hydrogen buses will have become irrelevant.

With all the advantages and disadvantages of hydrogen buses in a row, we can start looking to the future. According to experts, hydrogen buses will indeed play a role in the public transport of the future. It will probably not be a battle between hydrogen buses and electric buses, but rather a combination will be sought. This will have to be done, as from 2030 all buses in public transport must be completely emission-free.



*Are there also smaller hydrogen-powered vans?
Follow the link for additional information.*



12.4 Hydrogen-powered trucks?

After the first hydrogen cars and hydrogen buses are on the market, the advance of hydrogen-powered trucks is also expected. As with the buses, hydrogen trucks also often use a hydrogen tank, fuel cell and battery to get moving.

From the hydrogen tank, hydrogen is led to the fuel cell where the gas reacts with oxygen from the outside air. This releases electricity and water, with the electricity going to the battery in the truck and the water leaving the truck through the exhaust. Just like with electric vehicles, a hydrogen truck also needs a battery to move forward.

Another possibility are trucks with a hydrogen-powered combustion engine, but this technology still needs to be further developed to really play a role in the transport world.

Yet you don't hear much about electric trucks for 1 important reason as with the buses: the weight of the batteries. These are too heavy to provide large vehicles with enough power to drive long distances.

In addition, it takes too long to charge electric trucks. To compare with hydrogen trucks, you can use a Fill up a hydrogen-powered truck with 80 kg of hydrogen in 15 minutes, you can drive 800 – 1000 kilometres with this. Charging an electric truck, on the other hand, takes several hours. In the transport world, time = money, which is why other sustainable alternatives were looked at, one of which is hydrogen-powered trucks.

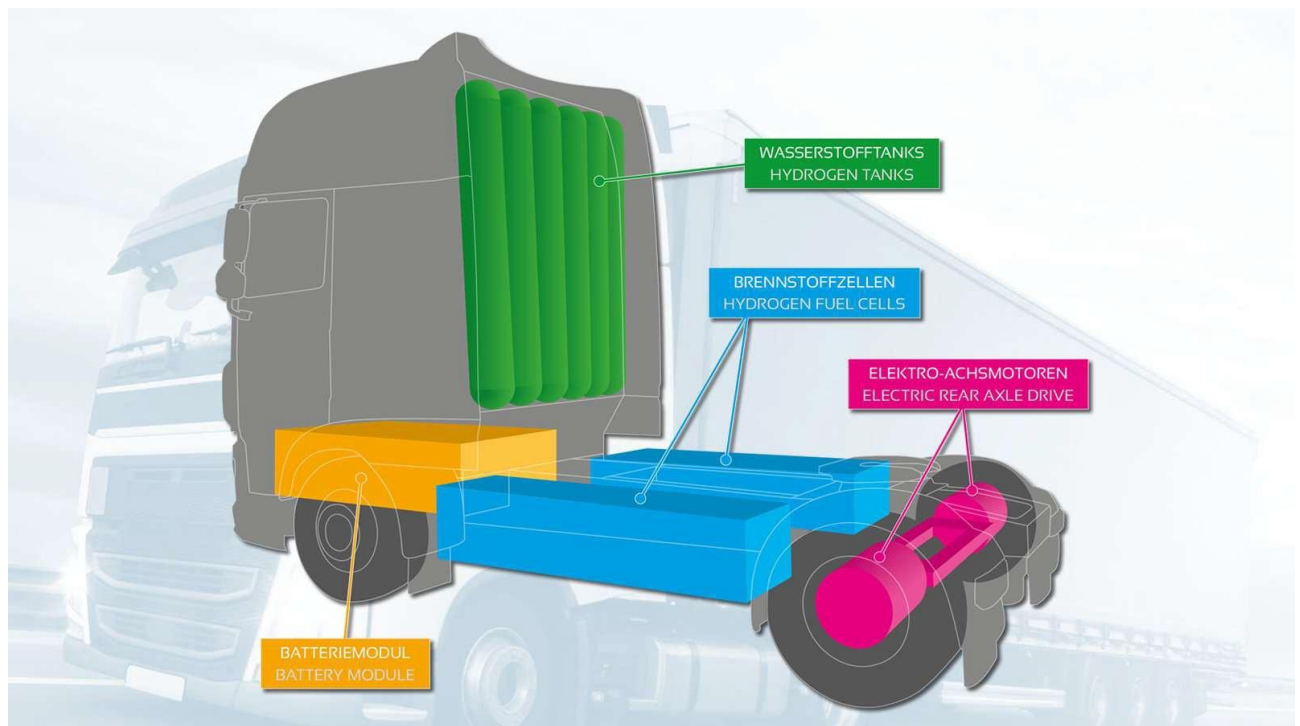
Hydrogen trucks can therefore refuel faster than electric trucks can charge and have a longer range. But what about the cost of these trucks?

A hydrogen-powered truck is a lot more expensive to buy than alternatives. For example, a truck costs about 700,000 euros. This is very pricey when compared to a diesel truck (= 100 000 euros) and an electric truck (= 250 000 euros). Refuelling costs are also higher than with diesel or electric trucks.

A bright spot for hydrogen-powered trucks is maintenance. This has not yet been tested in practice, but everything indicates that a hydrogen truck is just as expensive to maintain as the alternatives. This is because these trucks are not much more complicated inside. There are even fewer moving parts that can wear out in a hydrogen truck than in a diesel truck, which even indicates that they are cheaper than diesel trucks.



Hydrogen-powered truck from MAN with the arrangement of the tanks.



Schematic representation of a hydrogen-powered truck.

Advantages of hydrogen-powered trucks:

- Refuelling takes 15 minutes compared to hours (with an electric truck) and you can drive almost 1,000 kilometres on one tank. So you save **time** !
- Of the total CO₂ emissions worldwide, 6% of the emissions come from heavy trucks that transport our goods. By using **green hydrogen**, there will be no CO₂ emissions while driving, only water vapor. This can help us achieve the proposed climate goals.
- Because hydrogen trucks have about the same properties as electric trucks or other means of transport, you will **not be bothered by** noise or a smell. There is no emission.
- After testing with hydrogen trucks in Belgium, the drivers were asked about the driving characteristics and these were **positive**.
- Transporting a relatively unknown gas for us in a truck can sound dangerous. But with current technologies, this is not a problem. Trucks running on hydrogen gas are just as **safe** as with diesel or electricity.

Disadvantages of hydrogen-powered trucks:

- Electric and diesel trucks are much **cheaper**: it is a lot more expensive to buy a hydrogen truck and refuel it. Hydrogen is also about 8x more expensive per kilometre than with electric trucks.
- Currently , 90% of the hydrogen used in filling stations is produced using natural gas or petroleum = **grey hydrogen**. So this is still not good for the environment.
- The **infrastructure** is not yet ready for hydrogen trucks. There are not yet enough hydrogen filling stations in Europe for comfortable transport.
- Hydrogen may become obsolete if electric trucks continue to develop. This is a disadvantage for hydrogen-powered trucks. Because the development of electric trucks is not standing still, batteries are becoming lighter and longer ranges, perhaps hydrogen will become superfluous in the future.

Despite the fact that there are currently no commercial trucks on the market, there are a number of brands that are working on the development such as Volvo, Hyzon and Hyundai.

Volvo's hydrogen truck is currently in the development phase. Volvo expects their hydrogen truck to be commercialized in the second half of this decade.



*The Volvo group is looking to the future, with 2050 in particular.
Follow the link for additional information.*



Hyzon is still an unknown brand that is also in the process of development. The company was founded in 2019 from a Horizon Fuel Cell Technologies. This company has been producing hydrogen agents for 18 years. The fuel cells in Hyzon's trucks are the most energy-dense of all other brands.

Hyundai's hydrogen trucks are currently the furthest along in development. A downside to Hyundai's XCIENT series is that the range is only 400 kilometres. Compared to Volvo's trucks with a range of 800 - 1000 kilometres, this is a big difference!

Despite the fact that some major players in the automotive world are busy developing hydrogen trucks, it remains to be seen whether hydrogen trucks will really be a success. For the time being, there is still talk of a large proportion of grey hydrogen: about 90%.

The production of hydrogen gas remains expensive and electric trucks are developing at lightning speed. As a result, it is still difficult to say whether hydrogen trucks will be a success. This is also because the development of these trucks is still heavily subsidized by the national and continental governments. If this money tap is turned off, it is doubted whether so much money is still being invested in R&D (research & development).

13. HYDROGEN IN SHIPPING

In the world of sustainable shipping technologies, hydrogen is currently taking centre stage as a promising solution to transform the maritime industry.

Hydrogen-powered ships are on the rise, as they offer an environmentally friendly and efficient alternative propulsion to traditional marine fuels.

A hydrogen-powered ship works according to an ingenious process that starts with the storage of gaseous hydrogen in solid cylinders. The cylinders are held under an immense pressure of 350 to 700 bar, while the temperature drops to -253° C, pressing hydrogen into a compact form.

The next step in this complex system involves the transport of hydrogen gas via a regulator to the fuel cell on board the ship. A crucial chemical reaction takes place in this fuel cell. Here the hydrogen comes into contact with oxygen that is extracted from the air. This encounter results in the generation of electricity, a fundamental step in the process.

This electricity serves as the lifeblood of the ship, as it powers the electric motor responsible for moving the propellers. The ship moves forward, powered by this clean and efficient energy source.

In addition to fuel cells, alternative technologies are also being explored, including hydrogen engines, which work in a similar way to traditional diesel engines, but use hydrogen instead of diesel. In addition, there are hydrogen combustion engines that burn hydrogen gas in air, which is also a possible approach to fuel ships. This diversity of technologies demonstrates the maritime industry's commitment to developing sustainable and efficient solutions for the shipping of the future.

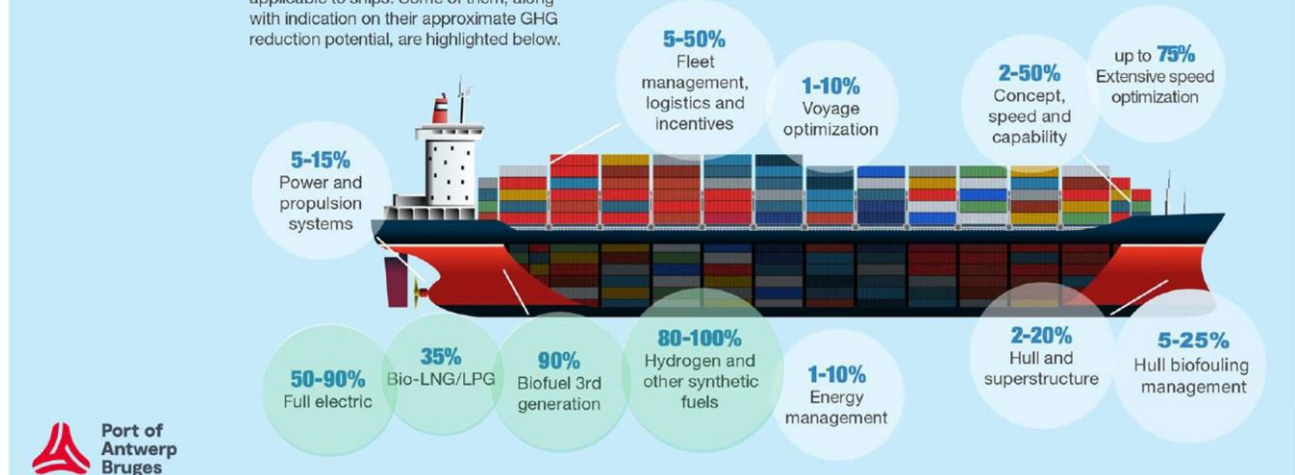
There are several reasons for widely deploying hydrogen ships in the maritime world, but the biggest reason has to do with the environment. Every year, 11% of CO₂ emissions come from the transport sector, 36% of which is caused by inland and maritime shipping. Ships and boats are therefore mega emitters. To change this, we need to look at eco-friendly ways to sail, and this is where hydrogen comes in.

How to reduce CO₂ emissions in shipping?



A wide variety of design, operational and economic solutions

Achieving the goals of the Initial IMO GHG Strategy will require a mix of technical, operational and innovative solutions applicable to ships. Some of them, along with indication on their approximate GHG reduction potential, are highlighted below.



But why don't we go electric? This is simply not possible on a large scale because large ships need enormous power. If you want to run cargo ships on batteries, you would need so many heavy batteries that no more cargo can be carried on the boat. In addition, it would take days, weeks or even months before you can fully charge a boat and the range is very short.

As with other means of transport, hydrogen-powered ships have advantages and disadvantages.

Advantages of hydrogen ships:

- Hydrogen ships running on **green hydrogen** do not emit CO₂.
- Ships that run purely on electricity need so many heavy batteries that this is at the expense of the charging capacity. A property of hydrogen is that the gas is very energy-dense, so transporting this gas is not very much at the expense of how much cargo you can take with you.
- Refuelling takes the same time as for diesel-powered ships, where it will be done in a safe and efficient manner.
- Hydrogen-powered ships make hardly any noise and do not stink. This is especially advantageous for hydrogen-powered inland vessels. This way you are not bothered by the diesel stench and the noise of a heavy ship.

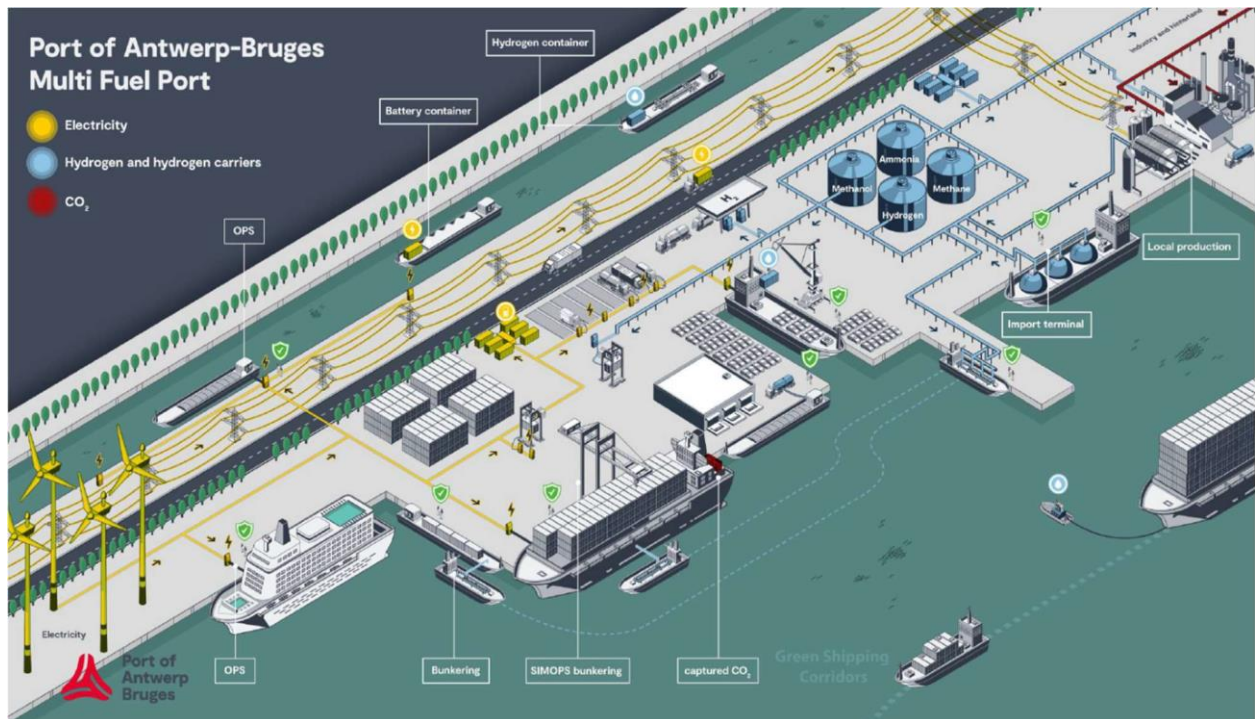
Disadvantages of hydrogen ships

- Hydrogen gas is a lot **more expensive** than diesel.
- Currently, the majority of hydrogen is considered grey with **CO₂ emissions still** being produced.
- If this money tap of **subsidies** is turned off by the government, this can cause a stagnation in development.
- Even if hydrogen gas is declared safe enough, it must be handled with care because the gas is highly flammable. The chance is small, but if something goes wrong, it can cause a disaster.

In conclusion, hydrogen-powered ships offer a promising future for the maritime industry, with their clean and efficient propulsion technologies. While there are challenges in terms of infrastructure and cost, the environmental and sustainability benefits are clear, making them an attractive choice for the shipping industry looking for greener solutions. Port of Antwerp – Bruges is fully committed to this...



CMB. TECH is one of the most innovative companies in the field of shipping in Port of Antwerp - Bruges. More information? Follow the link.



In Norway, they are experimenting extensively with hydrogen ferries, which is understandable given that nowhere else in the world is there as much transport via waterways as in Norway and the wider Nordic region. By 2025, the first hydrogen boats, 85% powered by green hydrogen, will sail on the most popular routes.

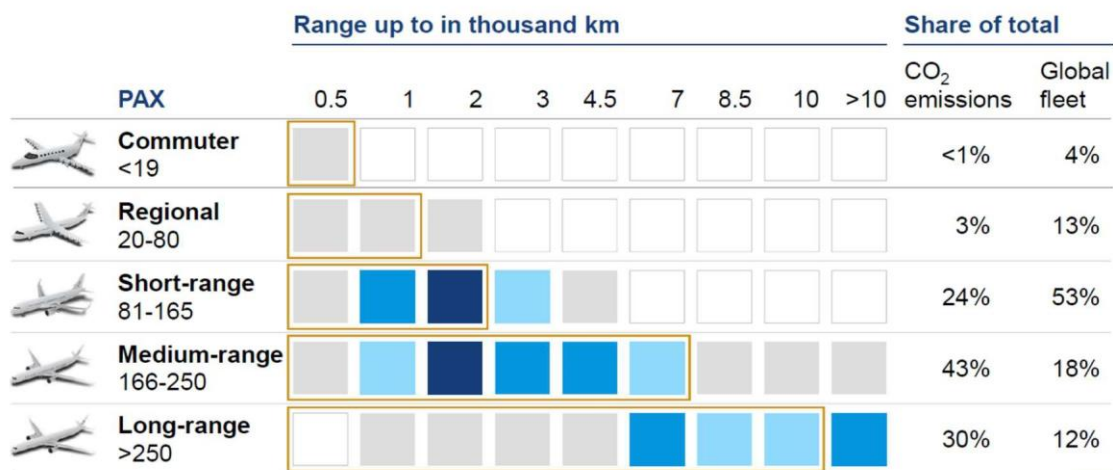
These Norwegian ferries have a capacity of almost 600 cars, and the use of these hydrogen boats is estimated to lead to a reduction of 26 000 tons of CO₂ emissions. This corresponds to the emissions of 13,000 diesel cars during a year.



*Will we see these ferries back in Belgium in a few years' time?
Follow the link for the prototypes from Norway.*

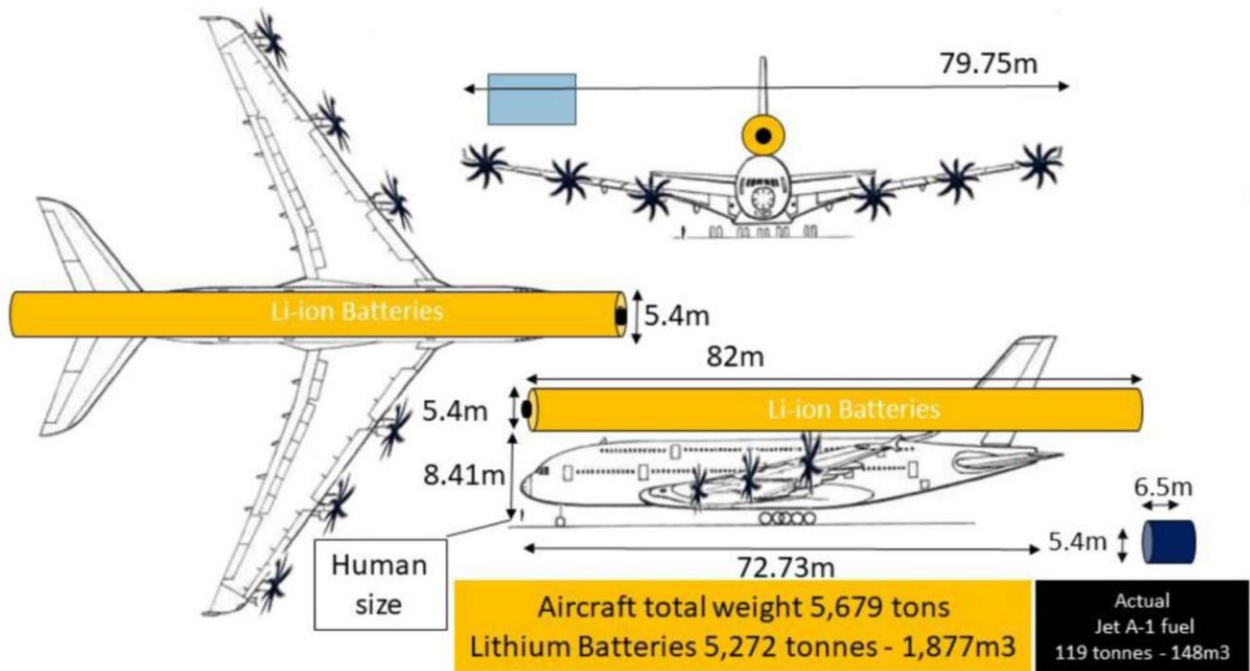


14. HYDROGEN IN AVIATION



Looking at the above data, it is no surprise that kerosene-powered aircraft emit a huge amount of CO₂. In 2022, the entire aviation sector was responsible for 2% of the world's total emissions. This doesn't necessarily sound like much in the big picture, but in 2019, aircraft emissions were 80% lower. If this development continues, the environment will be seriously affected. Aircraft running on green hydrogen can slow down this development.

But why don't we use electric planes? An aircraft needs an enormous amount of power to move. So to move planes, an enormous source of energy is needed. If you want to fly electrically, you have to take so many batteries with you that the plane barely gets off the ground due to the weight. This can be clearly seen in the next figure.



As a result, batteries with electricity are only an option for smaller vehicles such as scooters, motorcycles and cars. Hydrogen planes therefore offer an alternative to electric planes due to the much lighter hydrogen gas.

Since hydrogen planes are not yet mass-produced and used, we cannot yet accurately say how much hydrogen planes cost. However, we can take a look into the future and estimate whether flying on hydrogen will be cheaper than on kerosene. However, it is important to say that the production of the aircraft themselves is only one of the costs that must be taken into account. The cost of hydrogen gas production itself and the entire infrastructure have a much greater impact.

According to a feasibility study, almost 300 billion euros will be needed between 2025 and 2050 to build and develop a working hydrogen infrastructure for hydrogen aircraft. Only 5% will go to the development of the aircraft themselves, 12% to the infrastructure of the airport, 6% to the distribution of hydrogen and 54% to hydrogen production. The development of the hydrogen aircraft themselves is therefore relatively inexpensive, but producing enough green hydrogen gas is.

Nevertheless, hydrogen planes are expected to be more than 2% cheaper than kerosene planes by 2035, provided they are sufficiently taxed. At the moment, there are hardly any excise duties on kerosene, but in the future it is expected that this will happen to prevent serious environmental disasters.

Advantages of flying on hydrogen.

- Green hydrogen offers an opportunity for **CO2-free** flying.
- Flying on hydrogen is **more advantageous** in the long run.
- Hydrogen gas can easily be stored for **a long time**. Unlike other green energy sources such as electricity from solar panels or wind turbines, you can store hydrogen for long periods of time without much energy loss. This allows you to supply more hydrogen gas at times when there is more flying and vice versa.
- Flying on hydrogen makes **less noise**, which means there is less nuisance in the vicinity of an airport.

Disadvantages of flying on hydrogen.

- Hydrogen gas is currently **a lot more expensive** to manufacture than kerosene. It is therefore not yet financially responsible to fly on this gas.
- Grey hydrogen also emits **CO2**.
- Hydrogen is highly flammable and colourless, so there are still working points for **safety**. Leaks cannot be seen with the naked eye and one small mistake can mean a catastrophe.

However, technology in the field of hydrogen continues to develop constantly.

Innovation Challenge: Ultra-efficient Aircraft Architectures



Ultra-performant wings



Propulsion integrated in airframe for low noise



Blended wing architectures



Aircraft architectures with integrated hydrogen tanks



Zero-e Hydrogen Combustion Demonstrator



The future of aviation is currently in the R&D departments. Some prototypes can be found above, but not yet in the air. In space travel, on the other hand, it is already being used.

Today the Boeing CST-100 Starliner has finally been successfully launched. An Atlas launcher using liquid hydrogen as fuel was used for the launch.



The Starliner is a reusable spacecraft that made its first test flight in December 2019. Today, the capsule was launched for the first time as a manned flight. The trip goes to the ISS space station under NASA's Commercial Crew-Contract.

At this launch, 2 experienced astronauts are on board: two experienced astronauts selected: Sunita Williams and Barry Wilmore. The Starliner normally accommodates four and up to five astronauts and must be able to remain docked to the ISS for a maximum of 210 days.

The Starliner is suitable for launching on various carrier missiles, such as the Delta IV, Atlas V, Falcon 9 and the Vulcan under development. For this launch, the choice fell on the 20-year-old Atlas V from United Launch Alliance (in which Boeing has a 50% stake). When the Vulcan (which made its first flight in 2024) has proven itself sufficiently as a successor, it may take over that role.

The Atlas rocket uses hydrogen as rocket fuel. Or more specifically, the rocket uses Hydrolox. This is a combination of liquid hydrogen and liquid oxygen, which is slightly more hydrogen than oxygen in a typical mixture to keep the temperature in the combustion chamber lower. Hydrolox is considered the most efficient rocket propellant combination, with an average specific impulse of about 450 seconds. The average specific impulse is basically how much energy the fuel has per unit of propellant. In comparison, kerox engines use Rocket Propellant 1 (RP-1), a form of kerosene, and liquid oxygen. They have an average specific impulse around 350 seconds.

The Atlas launcher is not the only rocket that uses Hydrolox. The Merlin 1D on SpaceX's Falcon 9 and the future Vulcan launcher also use this mixture of liquid hydrogen and liquid oxygen.

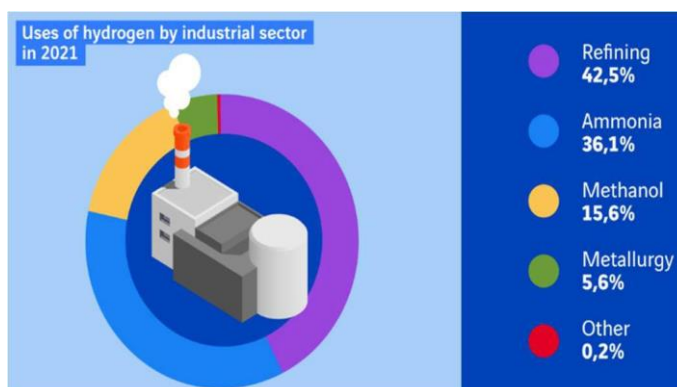
Source: Boeing Space

15. HYDROGEN IN INDUSTRY

In industry, molecules are often necessary for high-temperature heat or energy-intensive production processes, for example. Natural gas molecules are now used for this. The aim is to convert this into green molecules, in particular green hydrogen, as quickly as possible.

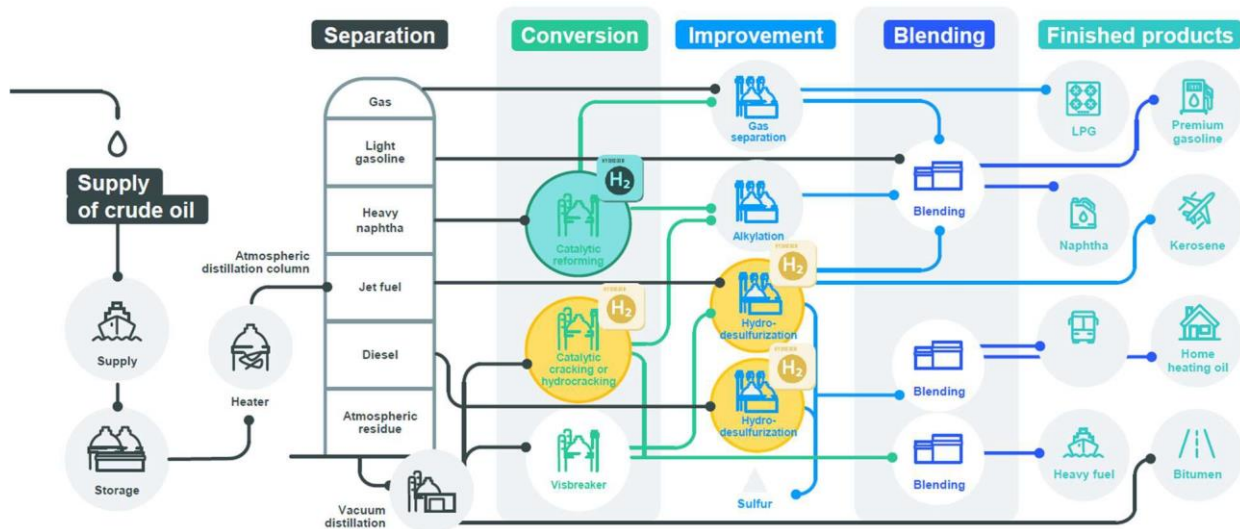
In addition, part of industry needs hydrogen as a raw material for materials or products.

In the **chemical industry**, hydrogen is already needed in the synthesis of chemical products.

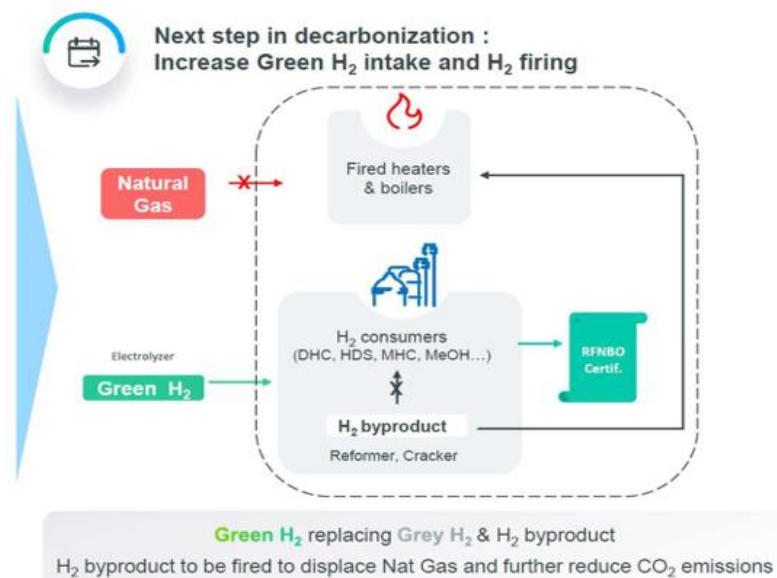
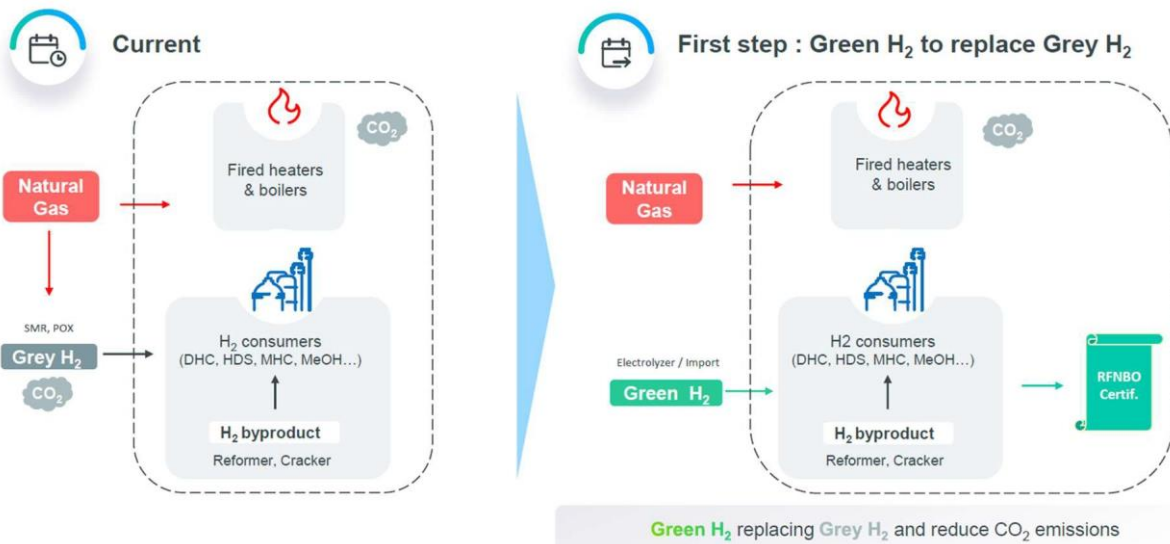


If we want to get rid of chemical processes based on fossil hydrocarbons such as coal, petroleum or natural gas, the need for green hydrogen will only increase.

We have to realize that the industry not only has to switch from fossil to affordable green molecules, but that the same industry demands that these molecules are available at any time and in any desired quantity. From that perspective, too, accelerated and large-scale deployment of hydrogen is important. After all, just like the fossil gas molecules, green hydrogen can also be stored and transported. This keeps our energy system affordable and in balance, while helping the large consumers of molecules get rid of their undesirably large CO₂ footprint.



Schematic representation of refining – process of hydrogen. Source: TotalEnergies.



Renewable hydrogen is a first step towards decarbonizing refineries.

15.1 Production of ammonia

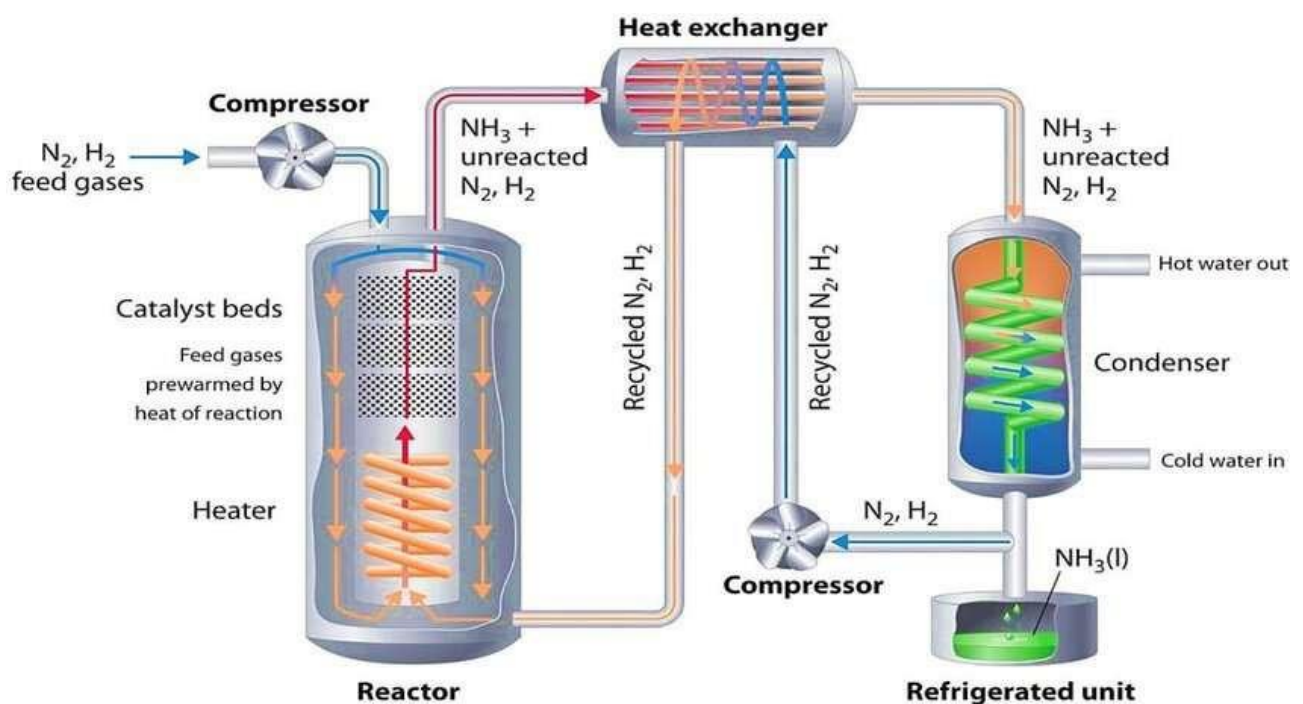
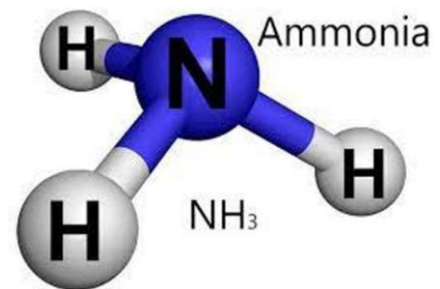
Ammonia is a chemical compound of nitrogen and hydrogen, with the formula NH_3 . Ammonia is a colourless gas with a pungent odour, which is widely used as a raw material for fertilisers, cleaning products and refrigerants.

It can be produced from water and air, using electricity. If the electricity comes from sustainable sources, such as sun or wind, then the ammonia is also **sustainable**.

We have seen hydrogen produced through electrolysis, which splits water into hydrogen and oxygen.

The hydrogen is then combined with nitrogen from the air to form ammonia.

This process is called **ammonia synthesis**. The ammonia is then stored in liquid form. To do this, it is brought under a pressure of about 10 bar or cooled to a temperature of -33°C .



Schematic representation of ammonia synthesis according to the Haber-Bosch process.

This makes the transport and storage of ammonia much easier than that of hydrogen, which has to be kept under a much higher pressure. In addition, ammonia has a higher energy density than hydrogen, which means that there is more energy in a given volume. Finally, the ammonia is converted back into hydrogen through a process called **ammonia cracking**. The hydrogen can then be used to generate electricity.

Ammonia is considered a promising **energy carrier** due to several benefits. Some of the key **benefits** include:

- **Energy storage and transport:** Ammonia can be produced by combining nitrogen and hydrogen. It can serve as a storage medium for hydrogen, which is useful because hydrogen on its own is technically challenging to store and transport on a large scale. Ammonia is relatively easier to store and transport, making it a practical option for transporting hydrogen.
- **High energy density:** Ammonia has a high energy density, which means that it can contain a large amount of energy relative to its volume. This makes it efficient for storage and transportation, especially when

compared to some other energy carriers.

- Opportunity for **green production**: Ammonia can be produced in a sustainable way by obtaining hydrogen through electrolysis, which uses renewable energy sources such as wind or solar energy. In this way, ammonia can be considered a "green" energy carrier, which means that its production does not involve any CO₂ emissions.
- **Global transportation infrastructure** : A well-developed infrastructure for the production, storage, and distribution of ammonia already exists, mainly due to its use in agriculture and the chemical industry. This makes it easier to integrate ammonia as an energy carrier into existing systems.
- **Flexibility** in applications: Ammonia can be used for a variety of applications, including generating electricity, as a fuel for vehicles, and even as a feedstock in the chemical industry. This flexibility makes it a versatile energy carrier. When used as fuel, no CO₂ is released.

While ammonia has many advantages, there are also **disadvantages** and issues, particularly with regard to its safe handling and storage, as well as the large-scale production of green ammonia.

- **Toxicity**: Ammonia is toxic, both by inhalation and in contact with the skin or eyes. It can pose health risks to humans and animals. The safe handling, transport and storage of ammonia therefore requires special precautions and technologies.
- **Flammability**: Ammonia can be flammable when mixed with air and ignited. Although it is not a classic fuel, there are safety risks associated with its use, particularly in situations where it may be released.
- **Corrosiveness**: Ammonia is corrosive and can attack metals. This can cause problems in the design and maintenance of systems and infrastructure that use ammonia as an energy carrier.
- **Storage and transportation**: Efficiently storing and transporting ammonia can be challenging. For example, it has a higher density compared to hydrogen gas, but it also requires special pressure and temperature conditions for storage and transport.
- **Transition issues**: Integrating ammonia as an energy carrier into existing energy infrastructure and developing new applications can pose technical and economic challenges.

Ammonia production is expected to increase by 40% over the next 30 years, with hydrogen playing a crucial role in this expansion. Currently, the ammonia industry is responsible for 1.8% of global CO₂ emissions, providing a significant opportunity to reduce carbon emissions worldwide.

By using carbon capture, utilization and storage (CCUS) and renewable energy, clean hydrogen can be deployed in the industrial process, leading to a significant reduction in emissions. This enables the petrochemical industry to expand in a sustainable way. In addition, ammonia has potential as a storage medium for hydrogen, as it is easier to transport than liquid or gaseous hydrogen. For this reason, clean ammonia production projects are receiving more and more attention and funding.



There is a lot of research being done into the use of ammonia as a fuel in shipping. Follow the link for more information.

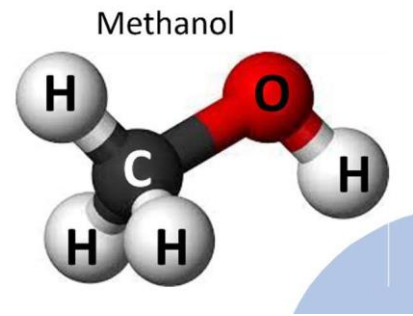


15.2 Production of methanol

Methanol, one of the most fundamental chemical substances, is produced on a large scale through various production methods. The production of methanol plays a role in the global chemical industry, as it serves as a base for countless other **chemical products**.

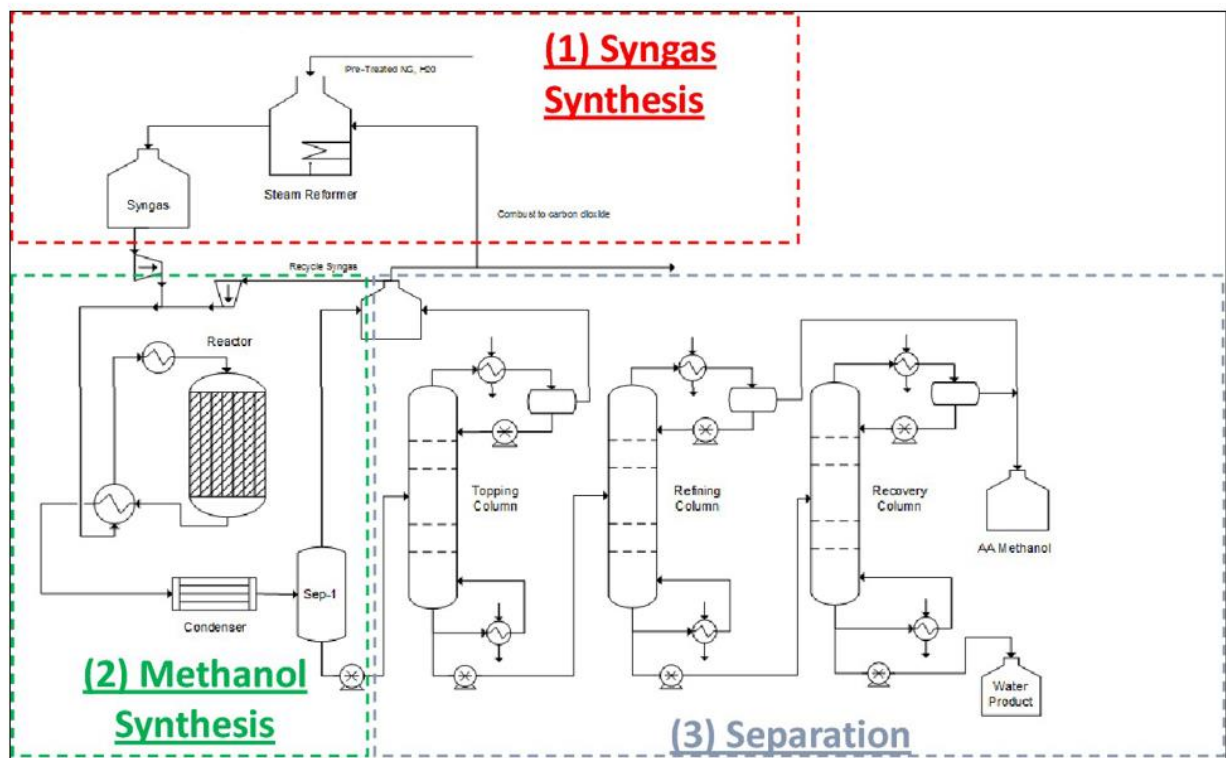
Most methanol produced worldwide starts with the production of synthetic gas, also known as **syngas**.

Syngas is a mixture of carbon monoxide (CO), carbon dioxide (CO₂), and hydrogen (H₂).



It is obtained by gasifying fossil fuels such as natural gas, coal, or biomass. The production process of methanol from syngas takes place in two main processes:

- **Steam reforming** of Natural Gas: The most common process starts with natural gas (methane, CH₄), which is converted into syngas by steam reforming. This involves heating methane and reacting with steam (H₂O) in the presence of a catalyst, usually nickel, to produce hydrogen and carbon monoxide.
- **Coal gasification**: In areas where natural gas is scarce, methanol can be produced by the gasification of coal. Coal is reacted with oxygen and water at high temperatures and under high pressure, resulting in the formation of syngas.



Schematic representation of methanol production.

Once the syngas is produced, **methanol synthesis** takes place. This is done in the methanol synthesis reactor, where syngas is converted into methanol via a catalytic process.

The process usually takes place under increased pressure and temperature in the presence of a copper or zinc oxide catalyst. During this process, the carbon monoxide reacts with hydrogen to form methanol. The reaction is

exothermic, meaning it produces heat, and the pressure and temperature must be carefully controlled to achieve the maximum yield of methanol.

After synthesis, the raw product contains mixtures of methanol, water and unreacted components such as carbon monoxide, carbon dioxide and hydrogen. Therefore, the raw methanol mixture is subjected to purification and distillation processes to obtain pure methanol.

- **Purification:** The first stage of purification involves removing gases and impurities from the raw methanol. This usually happens in a degassing column.
- **Distillation:** Next, the mixture is distilled to separate methanol from water and other impurities. This process can involve multiple distillation columns, depending on the purity required. The final product is usually methanol with a purity of 99.85% or even higher.

In addition to conventional methods, there are also **alternative** production methods for methanol production, but these are used on a smaller scale:

- **Biomass processing:** Methanol can be produced from biomass through gasification or fermentation processes. These methods are more environmentally friendly because they use renewable resources.
- **CO₂ conversion:** There are also processes in development that convert carbon dioxide directly into methanol, which is a promising technology in the context of carbon management and climate change. These processes use renewable energy sources to generate hydrogen, which is then converted into methanol using CO₂.

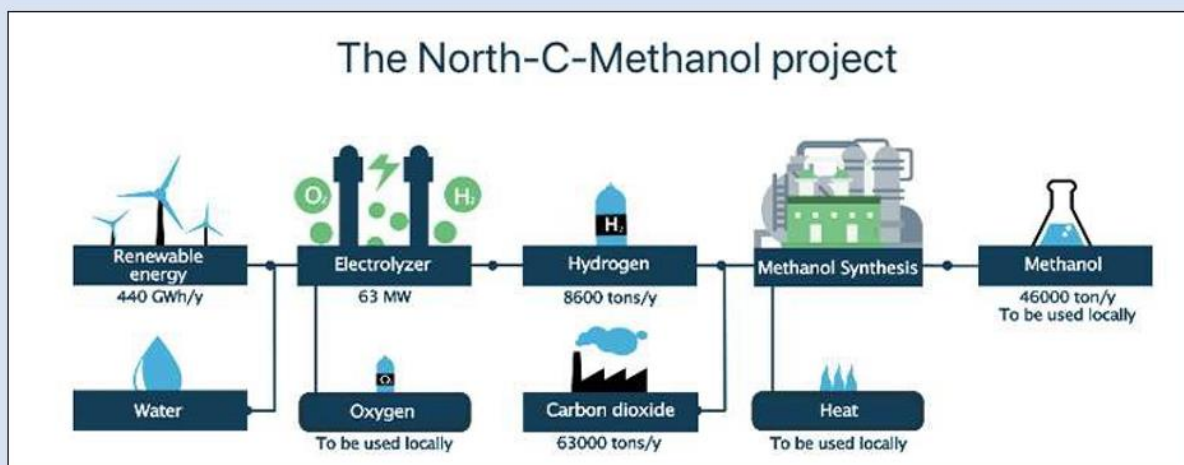


Methanol production has an impact on the environment, mainly due to CO₂ emissions and the consumption of fossil fuels. Innovations such as CO₂ conversion and methanol production from biomass are therefore becoming increasingly important in industry. These technologies reduce reliance on fossil fuels and help control the carbon footprint of methanol production.

In the North-C-Methanol project, two plants are being built on the Rodenhuijze peninsula in North Sea Port. One for the production of green hydrogen and the other for the production of methanol from hydrogen and captured CO₂.

Ten private and public partners have launched the North-C-Methanol project on the Rodenhuijze peninsula in North Sea Port. Two large-scale demo plants and supporting infrastructure will be built on the peninsula. The first installation, a 65-megawatt electrolyser, will be erected on the ENGIE site. This hydrogen plant will convert water into green hydrogen and oxygen via wind energy. The plant should be operational in 2024 and will scale up to 600 megawatts by 2030.

The second installation is a Proman methanol plant. This plant converts the green hydrogen from the electrolyser and CO₂ into green methanol. The CO₂ comes from large local industrial players such as ArcelorMittal and Alco Bio Fuel and is captured there in the production process. The local chemical industry and renewable fuel industry in turn uses the methanol as a green raw material and/or as a green fuel for ships and trains.



"This project shows why we can become a leader in sustainable innovation with Flanders. With our ports and their industry, we are ideally positioned to invest in a circular and sustainable industry. It ensures sustainable growth and new jobs, and with this type of project we are making a leap forward towards a resilient Flanders. Moreover, it is also a step towards becoming less dependent on fossil raw materials from abroad," says Hilde Crevits.

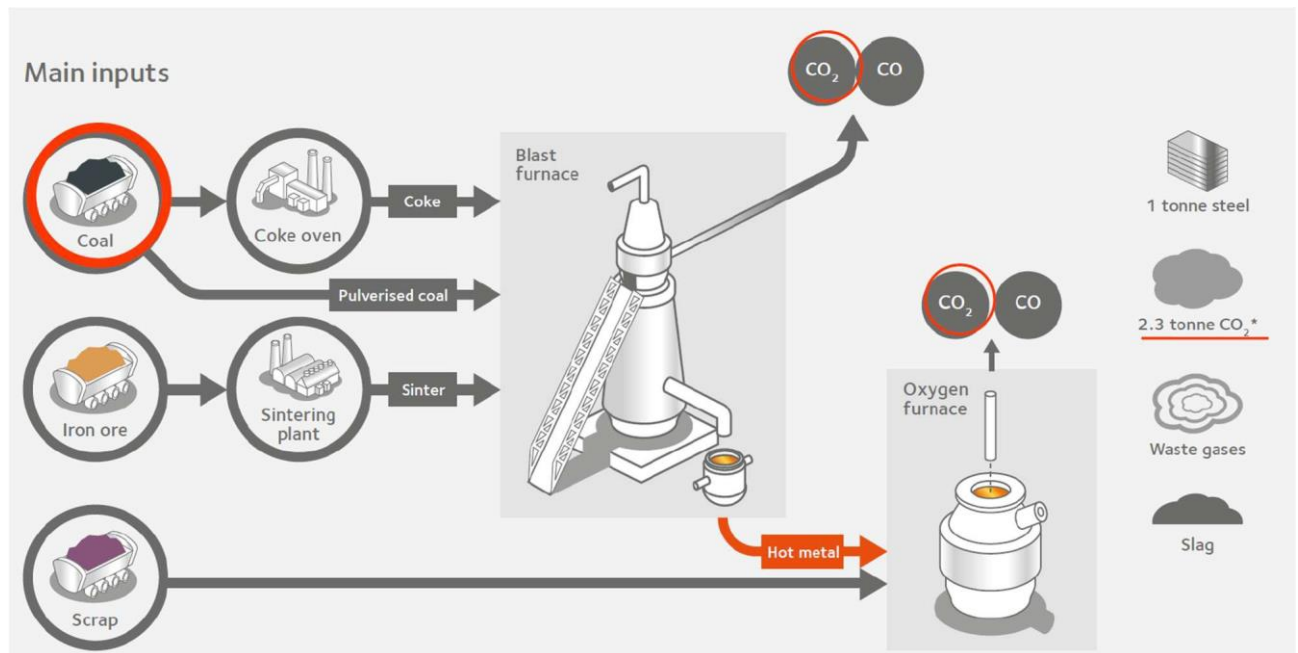


The North-C-Methanol project is part of the North-CCU-Hub. The Hub aims to achieve a total annual emission reduction of 1 million tons of CO₂ in North Sea Port in the long term. The animation below shows the development of the CCU/Hub.

Source: allesoverwaterstof.nl

15.3 Steel production

In steel production, there is increasing experimentation with the use of hydrogen to reduce emissions. Steel production requires high temperatures, traditionally using coal for both the heat and chemical reactions in the process.



Schematic representation of steel production with development of CO₂. Source: ArcelorMital.

Hydrogen can serve as a substitute in this process, both for the required heat and for the chemical reactions. When clean hydrogen is deployed, it offers great potential to reduce emissions, as steel is an essential building material for modern buildings and industrial processes.

Steel industry opts for hydrogen. Steel producers worldwide are working to reduce CO₂ emissions from their steel fabrication processes. Hydrogen can be of great service in this regard.

For example, the Swedish steel manufacturer SSAB, together with energy company Vattenfall and mining company LKAB, is having a real pilot plant built in the northern Swedish city of Luleå to investigate whether hydrogen can be used as a reducing agent in the production of ore-based steel. The hydrogen is used to replace coking coal, which is largely responsible for CO₂ emissions in steel production.

Traditionally, coking coal is burned to remove the iron ore from the ground into iron. Coking coal acts like a magnet that separates the oxygen atoms from the iron atoms. However, this also involves a bond of one carbon atom with two oxygen atoms. The greenhouse gas CO₂ was born, the emissions of which must be significantly reduced in the coming years. By exchanging coking coal for hydrogen, the process releases H₂O and much less CO₂.

The new Swedish production technology using hydrogen is called HYBRIT and should be fully developed around 2035 for the production of fossil-free steel, according to the so-called direct reduction process. The pilot plant is currently under construction / in Luleå, and completion is scheduled for this summer. Then the factory will be able to produce one ton of steel per hour according to the new process. In itself, that is only a fraction of the capacity of a conventional steel mill, about 250 tons of steel per hour. But the factory is primarily a research installation.

"The plant really serves to figure out how to get our process running," says Mikael Nordlander, head of Vattenfall's R&D department. "We got our hydrogen-based process working well in the laboratory in Stockholm, on a small scale. Now we want to achieve that in an installation that is one or two sizes larger. We will soon be able to play with important parameters, such as the exact composition of the reduction gas hydrogen, the temperature, flow rates and pressure levels. In this way, we learn how to enable a continuous process on a commercial scale."



In order to maximise the CO2 reduction, the use of green hydrogen is a must. Green hydrogen is hydrogen from sustainable electricity, generated via, for example, wind turbines and hydroelectric power stations. Grey hydrogen, made from natural gas, is not really an alternative. HYBRIT (of course) opts for 'green' and is helped by the local circumstances. In Sweden, most of the electricity required is already generated sustainably. Moreover, in Sweden there is 'a good balance between supply and demand. As a result, electricity prices are low, especially for industry,' says Nordlander 'The price of making hydrogen will also fall. In the future, more and more other industries will also need it.'

The new production technology has an additional advantage. The process with hydrogen also produces sponge iron. This intermediate product can be (re)used when recycling steel in an electric arc furnace.

To make HYBRIT a success, the Swedes are making substantial investments. 170 million euros have been invested in the current, first phase of the project alone. Of this, the Swedish government is raising about 50 million euros.

Source: bouwenmetstaal.nl



Read more? See

16. IS HYDROGEN SAFE?

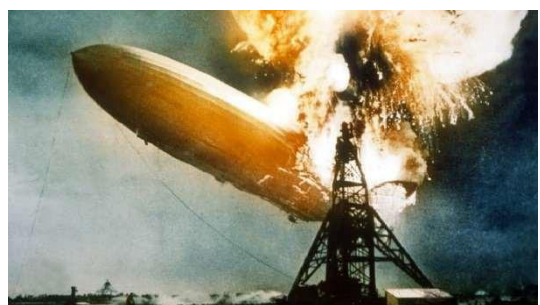
As with all fuels, the use of hydrogen entails risks. Hydrogen is no more dangerous than current fuels. We have to learn to deal with it on the basis of its properties, which are very different from those of fossil fuels.

Some of the risks of hydrogen are:

- Hydrogen is colourless, odourless and tasteless, which means that it cannot be noticed by a person.
- It can ignite in small amounts in the air.
- Little energy is needed to ignite hydrogen.
- Hydrogen can contain a lot of energy, so an explosion can be very powerful.
- Hydrogen is stored in tanks under high pressure, resulting in the necessary risks.

Hydrogen has been used on a massive scale within industry for decades and has a very positive safety history. Popular misconceptions such as the hydrogen bomb, which is based on nuclear fusion, and the Hindenburg disaster, where it turned out to be an ordinary zeppelin material fire, sometimes still do injustice to the perception of hydrogen.

Modern applications such as the hydrogen car and filling stations have also not yet experienced any calamities. Provided that we know and act on the properties of hydrogen, this is a safe energy carrier.



The safety risks of hydrogen mainly relate to the fact that it is often used at high pressure, that it has a low ignition energy and also burns with a flame that is not very visible. Hydrogen is also explosive in a wide

concentration range in confined spaces in the presence of oxygen and an ignition source.

The volatility of hydrogen also means that it tends to leak into certain sub-components such as pipes, pressure vessels or storage tanks. However, precisely because hydrogen is 14 times lighter than air, it rises at a speed of almost 20 meters per second. This is conducive to safety as it can be released quickly in the event of calamities such as fire, unlike conventional fuels or even batteries. After all, it does not just hang or lie on the flame, provided that drainage is possible at the top of the room.

So what we want to avoid at all times with hydrogen installations or applications are leaks and ignitions. Leaks are prevented by good choice of materials by manufacturers in accordance with the standard standards. Periodic maintenance is also very important. Systems can be provided with extra safety by building in gas detection and emergency stop systems. External impacts, such as collisions, are counteracted by, for example, concrete structures at petrol stations. Hydrogen tanks in vehicles pass grenade and bullet tests.

Inflammation is avoided in the first place through the use of common sense. Smoking is not allowed at hydrogen sites or other activities that can cause inflammation. With regard to fire safety, procedures must be followed such as providing fire walls, extinguishing valves, smoke detection, etc.

16.1 Recognizing Hydrogen Systems

Hydrogen can be stored in different ways: cylinders, tubes, tanks in a car,...

It is therefore important that this is recognizable to everyone: both users and emergency responders.

Transport of dangerous goods must be indicated by **international symbols and labels**:

- Red sign with symbol and number 2 = flammable gas (ADR code)
- The number 23 = flammable gas (GEVI code).
- The number 1049 = gaseous hydrogen under pressure (UN number).



The **cylinders** in which hydrogen will be stored are made of steel and the maximum pressure is 300 bar. A cylinder usually has a capacity of 50 Liters and contains about 1 kg of hydrogen. One can bundle 12 to 16 cylinders in a horizontal position so that one gets bundles. In such a **bundle**, the cylinders are all connected to each other.

Each bundle has 2 connections of which only 1 is used. A yellow indication will be visible on non-active connection. An empty hydrogen cylinder always contains hydrogen and is pressurized to prevent air from entering the cylinder.



Arrangement of bundles of hydrogen.