Skills for Hydrogen Safety

Erasmus+ KA202 - Strategic Partnerships for vocational education and training

Learning Unit 1

Hydrogen Basics

Contents

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-------- BLOCK 1 --------

1.1. Fossil Fuels

Fossil fuels are hydrocarbons, primarily coal, oil or natural gas, formed from the remains of dead plants and animals. They consist of buried combustible geologic deposits of organic materials, formed from decayed plants and animals. These deposits have been converted to oil, coal or natural gas by exposure to heat and pressure in the earth's crust for hundreds of millions of years.

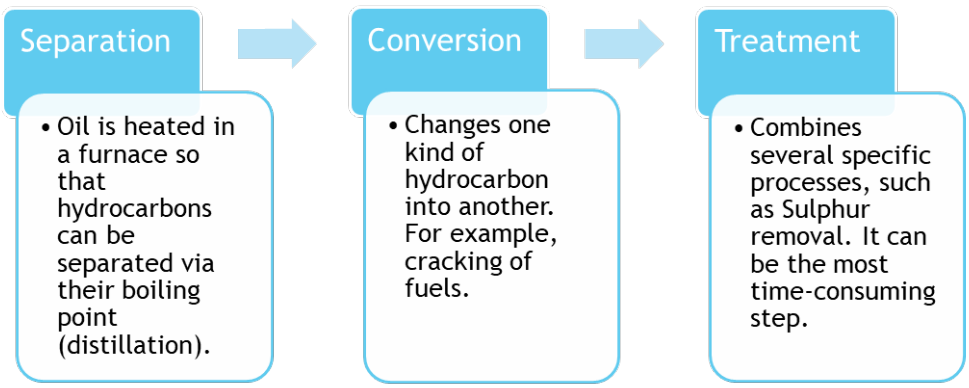
Fossil fuel use has enabled the Industrial Revolution and nowadays is by far the main source of energy in the world. The burning of fossil fuels by humans is the largest source of emissions of carbon dioxide – a greenhouse gas.

Fossil fuel are continually being formed by natural processes – however, they are non-renewable resources. This is due to the fact that it takes millions of years for them to form, and reserves are being used infinitely faster than they're being replenished. In other words, fossil fuels are not replenished naturally on a human timescale.

1.1.1. Petroleum

Petroleum, also called crude oil when in its natural form, consists of a mixture of hydrocarbons and other substances (mainly sulphur). Once extracted, refined and separated, oil produces a variety of products, including fuels, plastics, lubricants, wax, tar, asphalt and fertilisers, amongst others.

Petroleum refining is the process of converting crude oil into useful products, divided into three steps:



As of 2018, around 80 million barrels of petroleum are extracted around the world every day, with the United States, Saudi Arabia and Russia being the main producing countries.

Table 1. Top 10 oil producing countries in 2018 [Source: U.S. Energy Information Administration].

Country	Million barrels per day
United States	12.0
Saudi Arabia	11.1
Russia	10.8
Iraq	4.5
Iran	4.0
China	4.0
Canada	3.7
UAE	3.1
Kuwait	2.9
Brazil	2.5

1.1.2. Coal

Coal is an organic sedimentary rock composed of carbon and variable amounts of other substances. It is still the largest source of energy for electricity production in the world. There are four grades of coal, according to the amount of carbon it contains:

- ✓ **Peat**: earliest and youngest stage in coal formation;
- ✓ **Lignite**: also called brown coal, has a low carbon content and thus yields low energy;
- ✓ **Bituminous**: also called soft coal, it is the most common grade;
- ✓ **Anthracite**: also called hard coal, has a high carbon content and yields the highest energy.

As of 2018, approximately 7,700 million tonnes of coal are produced per day in the world, with China accounting for nearly half that amount.

Table 2. Top 10 coal producing countries in 2018 [Source: The British Petroleum Company plc].

Country	Million tonnes per year
China	3,523
India	716
United States	702
Australia	481
Indonesia	461
Russia	411
South Africa	252
Germany	175
Poland	127
Kazakhstan	111

1.1.3. Peat

Peat, also called turf, is found in mires or bogs, and is the first step in the geological formation of coal. Peat forms in wetland conditions because flooding obstructs the flow of oxygen from the atmosphere, slowing the rate of decomposition. It is a particularly inefficient fossil fuel, emitting considerably more carbon emissions than other fuels such as coal and natural gas.

Figure 1. Peat extraction.

Peat extraction (illustrated in Figure 1) presents a major environmental impact, and occurs mainly on raised bogs by stripping away the living layer and subsequently exposing large quantities of peat to facilitate oxidation and loss of carbon.

Peat production is confined to suitable areas and mostly consumed locally, with Finland and Ireland leading the world's production.

Table 3. Top 10 peat producing countries in 2013.
[Source: United States Geological Survey (USGS) Minerals Resources Program]

Country	Thousand tonnes per year
Finland	7,470
Ireland	6,600
Sweden	3,300
Germany	3,000
Belarus	2,970
Russia	1,500
Latvia	1,380
Canada	1,295
Estonia	927
Poland	760

1.1.4. Natural Gas

Natural gas consists of a hydrocarbon gas mixture, mainly methane (CH_4). It is found in underground rock formations and other reservoirs, and presents a variety of uses in areas such as electricity generation, heating, cooking, industry applications, chemicals production and transportation.

As of 2017, around 3,700 billion cubic meters of natural gas are produced worldwide per year, with the United States and Russia being the top producing countries.

Table 4. Top 10 natural gas producing countries in 2017 [Source: Enerdata Yearbook].

Country	Billion m^3 per year
United States	767
Russia	694
Iran	209
Canada	184
Qatar	166
China	147
Norway	128
Australia	99
Saudi Arabia	98
Algeria	95

Flaring, or burning off natural gas (illustrated in Figure 2), wastes around 3.5% of the world's production. This is usually done by companies to prevent a dangerous build-up, when there is a lack of equipment or money to capture the gas, or when the gas is contaminated with incombustible gases. Generally, it is much better to flare natural gas than to simply vent it, given that CO_2 has a global warming potential 21 times lower than CH_4.

Figure 2. Natural gas flaring.

1.1.5. The Problems of Fossil Fuels

Fossil fuels present a variety of environmental and social problems, which include the fact that they are:

- ✓ Carbon intensive: producing high amounts of Greenhouse gas (GHG) emissions, with catastrophic consequences in terms of climate change;
- ✓ Polluting: being responsible for an estimated 9 million deaths annually, causing countless diseases and loss of quality of life;
- ✓ Finite: at the current pace of usage, current levels will not last more than a few decades;
- ✓ Expensive: also referred to as "Pay-as-you-go" energy.

Discussion → An in-class discussion is recommended to highlight issues with fossil fuels and problems inherent to the current fossil-based energy infrastructure.

1.2. Greenhouse Gases and Climate Change

Greenhouse Gases (GHG) are gases that absorb and emit energy in the thermal infrared range. They trap heat in the atmosphere and are the main cause of the greenhouse effect.

The greenhouse effect is a natural phenomenon, vital to the existence of life on Earth – without it, the Earth's surface temperature would be around -18 °C. However, human activities in the last few centuries – fossil fuel use, deforestation, etc. – have strengthened the greenhouse effect, causing/increasing climate change.

The most common GHGs are:

- Carbon Dioxide (CO_2) → released by the combustion of fossil fuels and biomass, removed (sequestered) when absorbed by plants;
- Methane (CH_4) → emitted during the production of fossil fuels, from livestock and from the decay of organic matter;
- Nitrous Oxide (N_2O) → released by agricultural and industrial activities, and also by burning fossil fuels;

- Fluorinated gases → powerful gases emitted from several industrial processes.

Each gas's effect depends on factors such as concentration (e.g., current levels of Carbon Dioxide are 230 times higher than those of Methane), impact (e.g., CH_4 is 21 times more powerful than CO_2) and how long they stay in the atmosphere (which can vary from a few hours to thousands of years).

Climate change, in turn, relates to changes in the statistical distribution of weather patterns when that change lasts for an extended period of time. This can happen naturally, caused by natural processes such as volcano eruptions, variations in solar radiation, plate tectonics, etc., but becomes a source of concern when it is forced, caused by human activity – being then called anthropogenic change.

According to the National Aeronautics and Space Administration (NASA), by the beginning of the 21st century, the Earth's temperature was roughly 0.5 °C above the long-term average. Figure 3 presents this estimated variation.

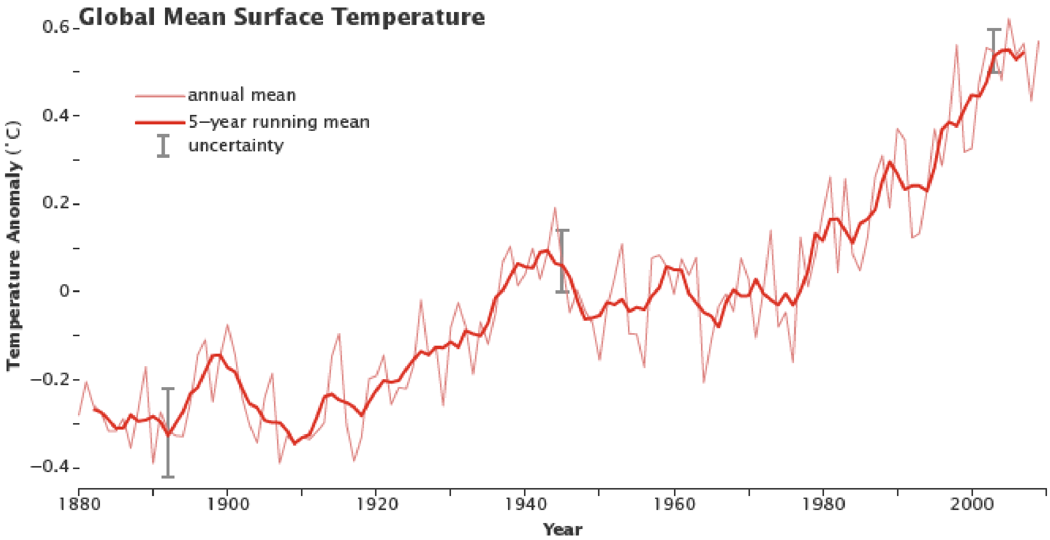


Figure 3. Variation in the world's average surface temperature [Source: NASA].

The consequences of climate change/global warming are many, including rising temperatures, which cause changes in vegetation, ecological imbalance and disturbances in terrestrial and aquatic ecosystems; challenges to agriculture and food production; changes in precipitation patterns, floods, droughts and heat waves; stronger and more frequent natural disasters; and melting glaciers and rising sea levels. In fact, some experts use the term Climate Emergency to emphasise the need for urgent change.

1.3. Renewable Energy

Renewable Energy relates to energy collected from renewable resources – this means that these resources are replenished on a human timescale. They are available in much wider areas, as opposed to fossil fuels, which are only found in some countries. Nowadays, renewables still contribute little (less than 20%) to our global energy consumption, and represent one of humanity's best tools to fight and mitigate climate change.

Well-known types of renewable energy include wind and solar energy, which are mature technologies that have experienced a considerable increase in popularity and correspondent decrease in cost in recent years. Other types of renewable energy include hydroelectricity, geothermal energy and biomass.

Discussion → An in-class discussion is recommended to identify and describe other types of renewable energy production.

Renewable energy technologies present a variety of environmental and social advantages, which include the fact that they are:

- ✓ Cleaner: emitting much lower GHGs, they help tackle climate change.
- ✓ Inexhaustible: a secure energy supply, that will not run out.
- ✓ Cheaper: although they require an initial investment, in the long-term renewables cost less.
- ✓ Good for everyone: bringing technological advancements and jobs in renewable energy projects.

1.4. Hydrogen

Hydrogen (H_2) is a non-toxic, highly combustible gas that does not produce carbon emissions after combustion – when combined with oxygen (O_2), it only produces water (H_2O). It is a versatile gas, and a valuable and important energy vector that can be a key component of a future low- or zero-carbon economy.

Hydrogen has the highest energy content by weight (33.3 kWh/kg) of any molecule, containing 3-4 times more energy than petroleum (12.0 kWh/kg), natural gas (13.1 kWh/kg) or coal (7.0 kWh/kg), as shown in Figure 4.

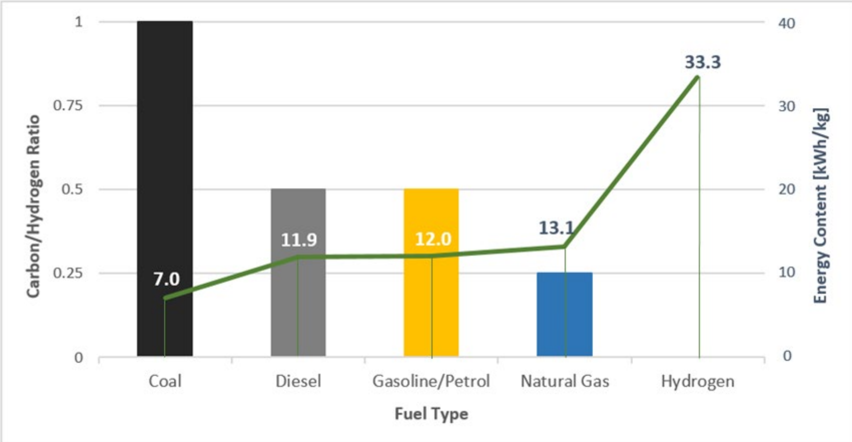


Figure 4. Comparison of carbon/hydrogen ratio and energy content by weight between hydrogen and other types of common fuels.

Hydrogen can be used for a variety of applications within the energy sector, ranging from electricity and heating to powering transport.

Hydrogen technology is not new. The first hydrogen powered vehicle was built in 1807 by French engineer François Isaac de Rivaz. Other vehicle prototypes followed, but the prominence of the oil industry – sustained by abundant resources and low cost – considerably reduced the mass visibility of hydrogen as a fuel. More recently, amongst the 1970's oil crisis and urges for cleaner emissions and general decarbonisation, hydrogen has again started to gain visibility.

The **hydrogen economy** is a proposed system of delivering energy using hydrogen as a zero-CO_2 emitting carrier. The term was coined by John Bockris in the 1970's, and reflects a strong interest in hydrogen as an energy carrier for several reasons:

- ✓ It can be distributed, combusted and used in the same way as fossil natural gas – given appropriate modifications;
- ✓ Electricity can be produced from hydrogen at very high efficiencies compared to traditional generation;
- ✓ Hydrogen can be produced from fossil, renewable and biomass sources, facilitating a bridging from carbon to a future zero-carbon economy, and this multi-pathway generation of hydrogen can be tailored to local circumstances and available resources;
- ✓ Hydrogen has zero tailpipe emissions after combustion, which facilitates lower cost CO_2 removal from the atmosphere in the future;

- ✓ Conversion from hydrogen to electricity is reversible, meaning that hydrogen is an analogue to electricity and it can provide an efficient electricity storage solution.

Recently, governments and organisations have been showing a growing interest in hydrogen technologies and increasingly invest in hydrogen projects. Also, a considerable number of publications on hydrogen strategies, insights and perspectives has been published in recent years.

However, despite growing global interest, hydrogen is still seldom used as a decarbonising solution. As presented in Figure 5, today, more than 90% of the current global hydrogen production (of around 70-80 million tonnes annually) relates to the needs of the petrochemical industry.

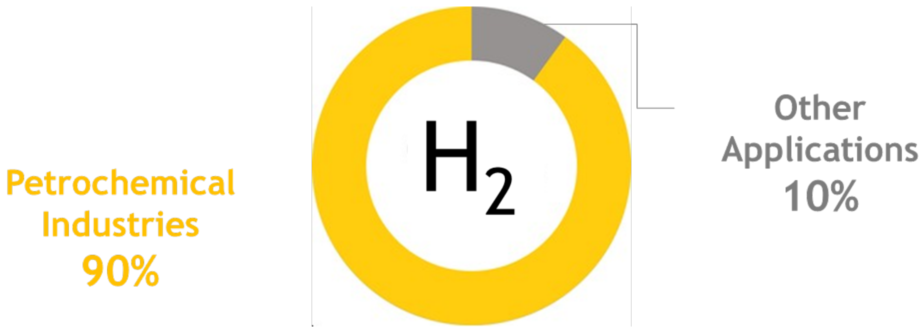


Figure 5. Only one-tenth of the hydrogen produced today is not used by petrochemical industries, with negligible amounts being used for decarbonising purposes.

Currently, half of the world's hydrogen is used to produce ammonia, mostly for agriculture. The remaining is absorbed by a miscellaneous group of industries, from fat hydrogenation to semiconductor processes.

Adding to the problem, the current global hydrogen production emits 830 MtCO_2eq (million tonnes of carbon dioxide equivalent) per year, because its feedstock is mostly fossil fuel based.

Discussion → An in-class discussion is recommended to identify roles that hydrogen can play in the much-needed energy transition, and to discuss the strengths and weaknesses of hydrogen as a decarbonising agent.

Suggested Reading → Hydrogen on the Horizon: Ready, Almost Set, Go?
https://www.worldenergy.org/assets/downloads/Innovation_Insights_Briefing_-_Hydrogen_on_the_Horizon_-_Ready%2C_Almost_Set%2C_Go_-_July_2021.pdf

CONTINUOUS ASSESSMENT 1:
PERSONAL REFLECTION

-------- End of Block 1 --------

-------- **BLOCK 2** --------

2.1. Properties of Hydrogen

Hydrogen (H) is the first and lightest element of the Periodic Table of Elements (Figure 6).

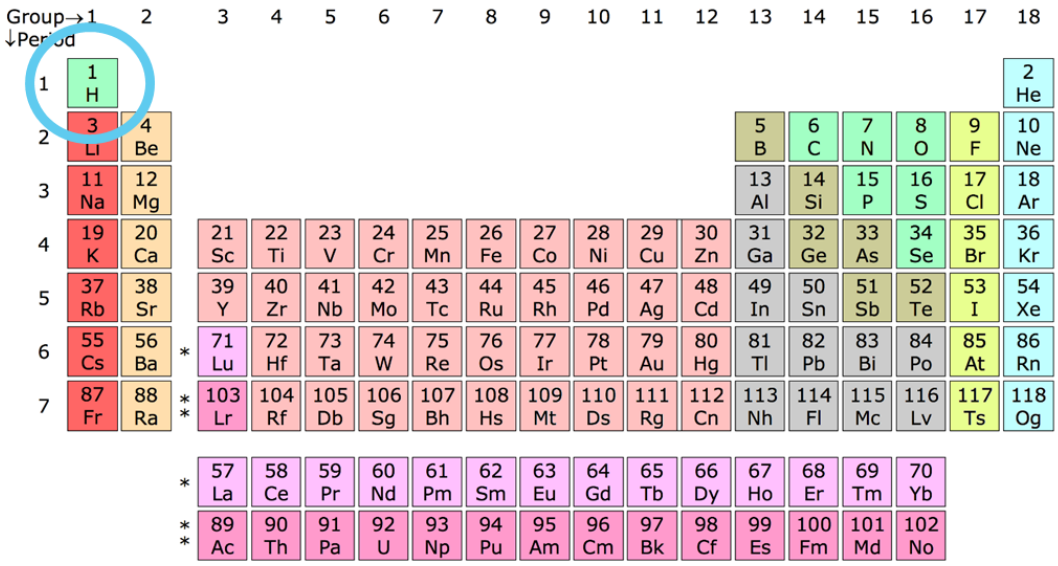


Figure 6. The Periodic Table of Elements, with the element Hydrogen highlighted.

The hydrogen atom is electrically neutral, containing one positively charged proton, one negatively charged electron and no neutrons. Hydrogen is the lightest and most abundant element, constituting approximately 75% of the mass of the universe.

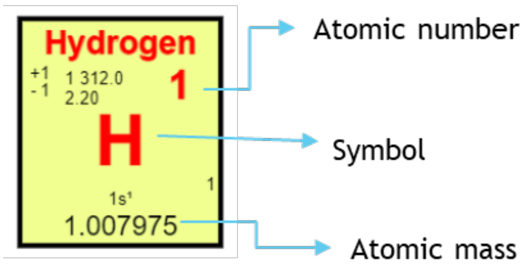


Figure 7. The Hydrogen element and its basic properties.

Atomic hydrogen is very rare on Earth, however. Hydrogen atoms tend to combine with other atoms in compounds, and with other hydrogen atoms to form Hydrogen Gas (H_2).

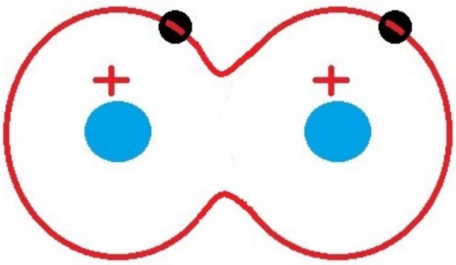


Figure 8. Basic schematic of the hydrogen gas molecule, with its two protons and two electrons.

Under standard temperature and pressure, hydrogen gas is non-toxic, colourless, odourless, tasteless, highly combustible and non-metallic. It is often called the “fuel of the stars”, since stars spend most of their lives fusing hydrogen, and our sun is mostly made of hydrogen.

Molecular hydrogen may react with a variety of elements and compounds – however, at room temperature, the reaction rates are so low as to be negligible. This means H_2 is virtually inert at room temperature, due to its high dissociation energy (the energy required to break the bond that holds the atoms together).

Hydrogen gas also has very low melting and boiling points, meaning it liquefies and freezes at extremely low temperatures.

Dissociation Energy (25°C) = 104.2 kcal/mole
Melting Point = - 259.2°C
Boiling Point = - 252.8°C

2.2. Hydrogen Production

Hydrogen can be produced using many methods, which present different levels of technology maturity, greenhouse gas emissions and environmental impact.

The most common production methods today are Steam Methane Reforming (SMR), Coal Gasification, Biomass Gasification and Water Electrolysis.

2.2.1. Steam Methane Reforming

SMR is the process of converting natural gas into hydrogen. It is by far the most common method of producing commercial hydrogen gas today, accounting for about 95% of the hydrogen used in the world.

Since it uses a fossil fuel, it is not a renewable technology. It is also not as clean as water electrolysis can be. However, fuel cell vehicles that use hydrogen produced via SMR still emit far less GHG than comparable gasoline-fuelled vehicles.

In SMR, steam reacts with methane in a reformer, at high temperatures (700 – 1100 °C) and in the presence of a metal-based catalyst, yielding carbon monoxide and hydrogen:

$$CH_4 + H_2O(g) \rightleftharpoons CO + 3H_2$$

The syngas exiting the reformer goes through a water-gas shift reactor that converts the CO into CO_2 and H_2 using the available water in the syngas (or additional steam that can be provided):

$$CO + H_2O(g) \rightleftharpoons CO_2 + H_2$$

The final step is the separation of the hydrogen from the syngas exiting the shift reactor, which can be done by a variety of methods. Overall, the production of 1 kg of hydrogen requires approximately 2.4 kg of methane as feedstock. Figure 9 summarises the method.

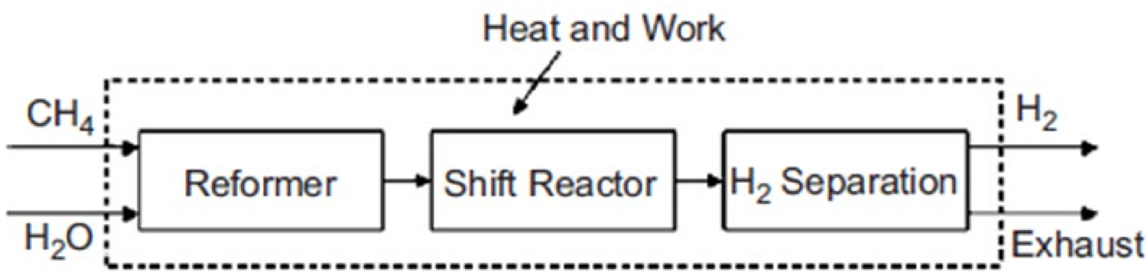


Figure 9. The Steam Methane Reforming process.

One of the main disadvantages of SMR is the high amount of carbon dioxide emitted in the process: on average, around 9 kg of CO_2 is produced for every kilogram of hydrogen. In fact, SMR facilities are responsible for about 3% of global industrial sector emissions of CO_2.

One solution that can help reduce or minimise this issue is Carbon Capture and Storage (CCS), or Carbon Control and Sequestration. This is the process of capturing waste CO_2 from large point sources and transporting it to a storage site where it will be deposited, preventing the release of large quantities of the gas. These sites are usually underground geological formations. CCS can reduce the amount of carbon emissions emitted by SMR systems and make the production of hydrogen via this method more sustainable.

2.2.2. Coal Gasification

In this method, coal reacts with oxygen and steam to produce hydrogen, carbon monoxide and carbon dioxide:

$$3C + O_2 + H_2O(g) \rightleftharpoons H_2 + 3CO$$

$$CO + H_2O(g) \rightleftharpoons CO_2 + H_2$$

It is also a method that uses a fossil fuel, and it is associated with large amounts of carbon emissions – up to 30 kg of CO_2 can be produced for every kilogram of hydrogen. CCS technologies can also be applied to coal gasification.

2.2.3. Biomass Gasification

Biomass Gasification, sometimes called Waste-to-Gas, sees hydrogen being produced from biomass feedstocks at high temperatures. The method produces variable rates of carbon emissions, but also addresses the issue of excess organic wastes generated by industry.

Despite producing GHG emissions, the method presents net-zero emission factors since it uses renewable/sustainable organic material as fuel. However, that may place pressure on land for food and other biofuels as well as biodiversity challenges.

2.2.4. Electrolysis

Water electrolysis is a process by which water molecules split into hydrogen and oxygen through the application of electrical energy. Hence, it is also referred to as "Power-to-Gas".

$$H_2O + \text{direct current electricity} \rightarrow H_2 + \tfrac{1}{2}O_2$$

It was the first commercial technology to produce pure hydrogen, dating back to the 1920s, and it is capable of producing hydrogen with no direct GHG emissions. However, due to the prominence of the fossil fuel industry and the established SMR infrastructure worldwide, only around 4% of the world's hydrogen production is based on electrolysis nowadays.

Electrolysis cells are the fundamental elements of the system. In each cell, a power source is connected to two electrodes – usually made from an inert metal – which are placed in the water. As the molecules decompose:

- Hydrogen appears at the cathode (where electrons enter the water);
- Oxygen appears at the anode (where electrons leave).

The cells can be connected in parallel or in series in order to form the electrolyser module. The hydrogen generated is cooled, purified, compressed and stored; while the oxygen is usually expelled to the atmosphere.

There are two main variations of the electrolysis process. In **Alkaline** electrolysis, a diaphragm separates the two electrodes, and the assembly is immersed into a liquid electrolyte (a solution of a basic substance such as KOH or NaOH). Hydrogen evolves from the cathode, where water is reduced yielding hydroxide anions (OH-). The anions pass through the diaphragm to the anode within the electric field, recombining to produce O_2.

Alkaline Electrolysis

Cathode:	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Anode:	$2OH^- \rightarrow ½O_2 + H_2O + 2e^-$

In **Proton Exchange Membrane (PEM)** electrolysis, a liquid electrolyte is not required – instead, it uses a gas tight thin polymer membrane. At the anode, water is oxidised producing oxygen, electrons and protons (which are in fact hydrogen ions). The protons pass through the membrane to the cathode where they are reduced, producing hydrogen gas.

PEM Electrolysis

Anode:	$H_2O \rightarrow ½O_2 + 2H^+ + 2e^-$
Cathode:	$2H^+ + 2e^- \rightarrow H_2$

Other variations also exist, however, Alkaline and PEM are the most mature and most easily available commercially. Figure 10 illustrates both variations.

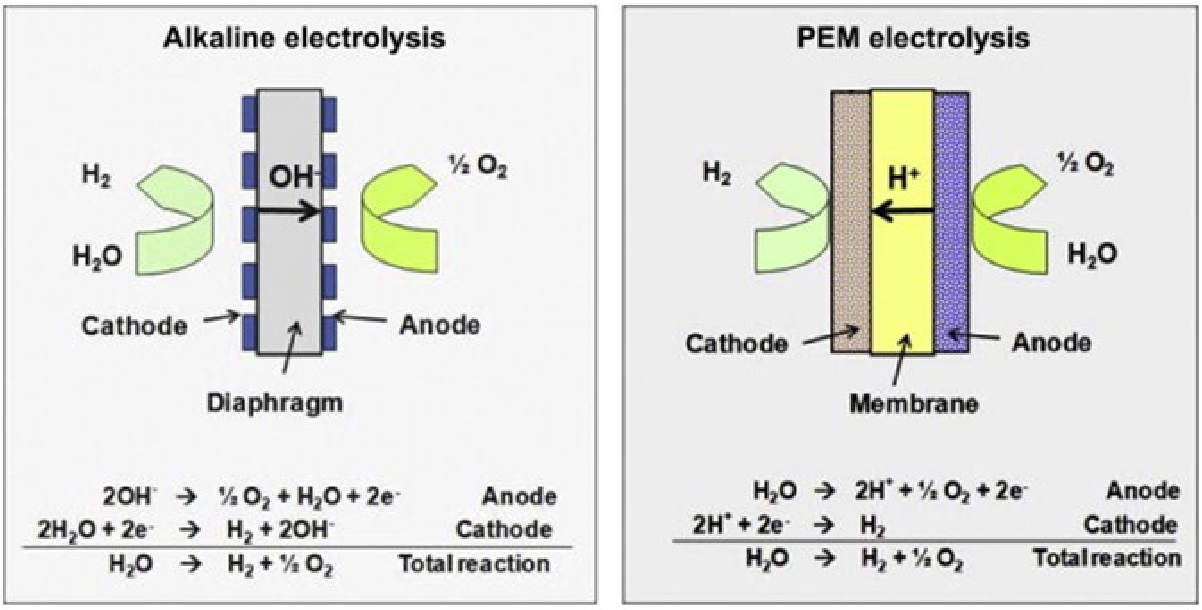


Figure 10. Alkaline and PEM electrolysis.

For any type of electrolysis, one key point that needs to be considered is the source of the electricity used: hydrogen produced via electrolysis can result in zero GHG emissions if renewable resources are used instead of the existing energy grid. Currently, in most countries, grid electricity is not the ideal source of energy because it is carbon intensive.

2.3. The Colours of Hydrogen

Despite being a colourless gas, different colours are used to identify hydrogen according to its production method and associated emissions. For example:

- ✓ When hydrogen is produced via electrolysis using renewable electricity, it is called **green** hydrogen;
- ✓ When it is produced via SMR, it is called **grey** hydrogen;
- ✓ However, when Carbon Capture and Storage is performed after SMR, it is then denominated **blue** hydrogen.

Table 5 lists the different colours of hydrogen, while Table 6 further details the carbon intensity and cost of the main methods of hydrogen production.

Table 5.The colours of hydrogen.

Colour code	Description	GHG Intensity
Black	Hydrogen produced using fossil fuel derived coal.	High
Brown	Hydrogen produced using fossil fuel derived lignite.	
Grey	Hydrogen produced using fossil natural gas (via SMR).	Medium
Blue	Hydrogen produced via SMR with CCS.	Low
Turquoise	Hydrogen extracted using the thermal splitting of methane.	Yields solid carbon
Green	Hydrogen produced using electrolysis powered by renewables.	Minimal
Purple / **Pink** / **Red**	Hydrogen produced used nuclear power as the energy source.	
White	Naturally occurring hydrogen.	

Table 6. Carbon intensity and cost of hydrogen according to its production method.

Production Method	Carbon Intensity [kg CO_2/kg H_2]	Cost [/kg H_2]	Cost with CCS [/kg H_2]
SMR (grey/blue hydrogen)	8.9 - 9.3	€ 1.17	€ 1.75
Coal Gasification (black hydrogen)	22.0 - 29.3	€ 1.29	€ 2.02
Biomass Gasification	2.7 - 32.8 (Net zero)	€ 2.09	€3.23
Water Electrolysis (green hydrogen - from renewable source)	< 4.4	€ 4.88	CCS not needed

Video → What Is Green Hydrogen And Will It Power The Future?
https://www.youtube.com/watch?v=aYBGSfzaa4c

Suggested Reading → Decarbonising end-use sectors: Practical insights on green hydrogen. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Coalition_Green_Hydrogen_2021.pdf?rev=ffd96aeed97c4d029b01aa3a93131e8b

CONTINUOUS ASSESSMENT 2: QUIZ

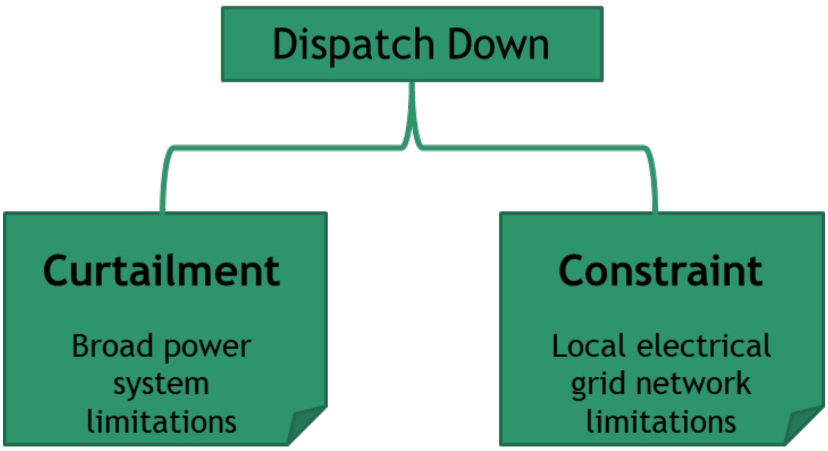
-------- End of Block 2 --------

-------- BLOCK 3 --------

3.1. Power-to-Gas

One of the main issues with renewable electricity such as wind and solar is the fact that it is inherently asynchronous and difficult to predict. For example, wind speed varies during the day and throughout the year; and insolation also depends on factors such as cloud coverage, location and seasonality.

Sometimes, renewables alone will not produce enough electricity to meet demand. Other times, the overabundance of renewables during periods of low energy demand will result in available energy that cannot always be absorbed by the system. This is known as the dispatch down of energy.



Discussion → An in-class discussion is recommended to highlight ways to store – and then use – excess renewable electricity that ends up being dispatched-down. Methods such as traditional batteries and pumped hydro (Figure 11) should be discussed and evaluated in terms of advantages and disadvantages.

Figure 11. Pumped-storage hydroelectricity.

In fact, an important role for hydrogen exists here: the variation in output of renewable electricity presents an opportunity for hydrogen as an energy carrier and storage medium. Dispatched-down energy has the potential to be stored and used through the adoption of Power-to-Gas (PtG) technologies.

Power-to-Gas is the process in which electricity is converted into chemical energy and stored in the form of a gas such as hydrogen. Hydrogen can be produced during off-peak periods or times when there is excess renewable electricity, instead of curtailing it. Then, that hydrogen can be used for grid balancing when there is increased demand, or delivered to other applications: it is a win-win situation.

In PtG systems, hydrogen is usually produced via water electrolysis, which means it is **green** hydrogen. Power-to-Gas systems can be a valuable decarbonising solution, presenting many advantages:

- Hydrogen is produced in a clean way with no associated GHG emissions (green hydrogen);
- Renewable resources will have reduced need for curtailment, and less excess energy will be wasted;
- The stored hydrogen will provide added security and balancing of the energy supply;

- There is also an opportunity to sell excess hydrogen for a variety of other purposes.

However, the technology poses a few challenges:

- High costs – PtG systems are still expensive to install and maintain, but they are becoming more and more cost-effective;

- Defining the optimal size and physical location of the electrolyser(s) is not always easy and requires strategic planning;

- The large amounts of hydrogen produced need to be stored somewhere.

Discussion → An in-class discussion is recommended to identify (preliminarily) how and where the large-scale storage of hydrogen can occur.

Case Studies → An opportunity to present existing and proposed Power-to-Gas systems across the world.

3.1.1. Electrolyser Basics

At the heart of most Power-to-Gas systems is renewable electricity produced through the electrolysis of water. The operation of electrolysers and the differences between Alkaline and PEM electrolysis were explored in Block 2 – a quick revision is recommended.

In practical terms, the main elements of an electrolysis cell are:

- ✓ The power supply (electricity);
- ✓ The input of water (H_2O);
- ✓ The outputs of hydrogen (H_2) and oxygen (O_2);
- ✓ The cathode (negative charge);
- ✓ The anode (positive charge);
- ✓ The diaphragm or membrane separating both sides.

Other elements might include pumps, vents, storage tanks and other components.

Lab Experiment → At this point a lab experiment is recommended so that learners can operate a small 64 W electrolyser. Instructions can be found at https://www.fuelcellstore.com/manuals/e206-e207-electrolyzer-65-230.pdf

3.2. Roles for Hydrogen in Heating

Beyond its role as an electricity storage medium, hydrogen can also play important roles in other areas of the energy sector, such as heating.

3.2.1. Residential and Commercial Heating

In regions of colder climate, the residential and commercial sectors typically require space heating – i.e., heating of spaces for human comfort – as well as water heating. Today, in most countries where space heating is required, this is generally provided through the burning of fossil fuels.

More sustainable alternatives are available to decarbonise residential and commercial heating, such as district heating. This type of local-level heating, illustrated in Figure 12, can be powered by a variety of renewable resources and is more efficient than individual boilers.

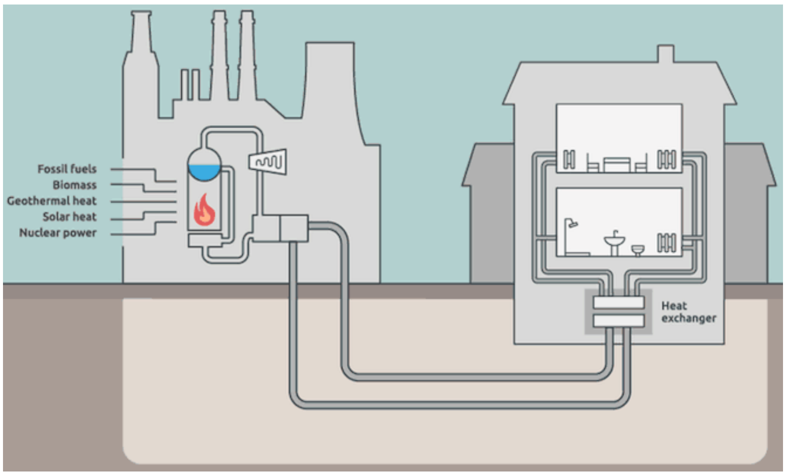


Figure 12. District heating animation.

Other sustainable alternatives also include heat pumps, when operating on clean electricity, and hydrogen, as a replacement for fossil natural gas.

3.2.2. Industrial Heating

When it comes to industrial heating, however, high-temperature heating is required for a variety of industrial processes. In this case, alternatives such as heat pumps and nuclear district heating cannot provide the high temperatures required.

Therefore, the combustion of a fuel gas is the most suitable solution for heating heavy industry. As an alternative to fossil natural gas (which is the standard today), green hydrogen arises as a highly combustible gas which is a low-carbon replacement for methane. However, large volumes of the gas are needed and, today, green hydrogen is still a high-cost option.

3.3. Roles for Hydrogen in Transport

Hydrogen has an important potential role in decarbonising yet another area of the energy sector: transport. As a fuel, it can be either converted to electricity in a fuel cell to power an electric motor, or combusted in an internal combustion engine.

Today, even though the fuelling network is still not widely developed, hydrogen-powered vehicles are commercially available in almost all European countries, the United States and many Asian countries.

Figure 13. The US's first pipeline-fed hydrogen fuelling station in Torrance, California.

3.3.1. Heavy Transport

Hydrogen as a fuel allows for long ranges and quick refuelling times, making it particularly attractive to large commercial vehicles operating long distances such as:

- ✓ Heavy Goods Vehicles (HGVs): Interest in hydrogen is gathering momentum amongst truck makers – Volvo, for example, expects half of its European truck sales to be hydrogen- or battery-powered by 2030.

- ✓ Buses: London is already served by at least twenty hydrogen buses, while Dublin has three hydrogen buses on its streets.

- ✓ Trains: Coradia iLint, the world's first hydrogen-powered train in Germany, can travel almost 1,200 km without refuelling.

Figure 14. The Coradia iLint hydrogen-powered train.

- ✓ Ships: Concepts of hydrogen-powered ships have been unveiled and are a promising solution for emission-free marine transport.

- ✓ Aeroplanes: Another hard-to-decarbonise sector, aviation will need to consider fuels such as hydrogen in order to cut emissions. One concept, the Airbus ZEROe, could enter service by 2035 – more info on https://youtu.be/5Fi65k2K3Mw

3.3.2. Light Transport

Light, short-range transport can also be powered by hydrogen. For instance, hydrogen-powered cars that are commercially available include the Toyota Mirai, in Figure 15, and the Hyundai Nexo.

Figure 15. The Toyota Mirai.

However, while hydrogen makes perfect sense for heavy transport, some question its superiority over a standard battery electric drive, in smaller vehicles. Considering losses associated with the production, compression and transport of hydrogen, combined with the limited efficiency of converting it back to electricity, the future of hydrogen in the context of light transport is not unanimous.

Suggested Reading → "Why Hydrogen Will Never Be The Future Of Electric Cars" by James Morris. https://www.forbes.com/sites/jamesmorris/2020/07/04/why-hydrogen-will-never-be-the-future-of-electric-cars/?sh=1e8f1dfd12fa

Discussion → An in-class discussion is recommended to analyse the suitability of hydrogen as a fuel for heavy and, particularly, light transport.

CONTINUOUS ASSESSMENT 3:
PRODUCTION OF AN ELECTROLYSER DIAGRAM

-------- End of Block 3 --------

-------- BLOCK 4 --------

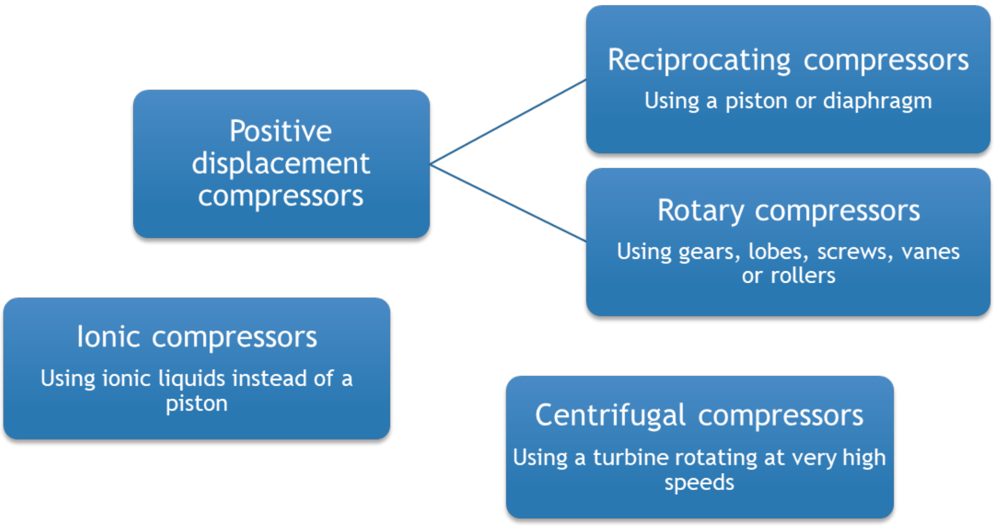
4.1. Compression and Storage of Hydrogen

Hydrogen can be stored aboveground as a gas; however, that requires compression – its density is so low that 1 kg of hydrogen at atmospheric pressure (1 atm) occupies approximately 12 m^3.

Hydrogen is normally produced at relatively low pressures (<30 bar), and compression is often needed directly after production. For example, 1 kg of hydrogen compressed to 100 Bar only occupies 0.13 m^3 – much less than the original 12 m^3.

Positive displacement compressors can be reciprocating or rotary. The former uses a motor with a linear drive to move a diaphragm back and forth, thus reducing the volume occupied by the gas through this motion. The latter, on the other hand, works through the rotation of gears, lobes, or rollers. A third variation of positive displacement compressors is also available: ionic compressors have a linear drive but use ionic liquids instead of diaphragms.

As for centrifugal compressors, they are usually the most suitable choice for pipeline applications due to their high throughput and moderate compression ratio. They operate by rotating a turbine at very high speeds to compress the gas, and must operate at speeds three times faster than that of natural gas compressors to achieve the same compression ratio because of the low molecular mass of hydrogen.



Compression costs are not insignificant – they actually represent most of CDS (Compression, Storage and Dispensing) costs. The impact of compression on hydrogen cost is twofold, comprising the cost of electricity to run the equipment and the capital cost of the compressor itself.

Compressing hydrogen allows it to be stored in composite tanks, such as the one shown in Figure 16.

Figure 16. A composite hydrogen storage tank.

4.1.1. Liquid Hydrogen

Hydrogen can also be stored aboveground as a liquid, at relatively low pressures and high energy density. However, cryogenic temperatures are required: as studied in Block 2, hydrogen's boiling point is very low (-253 °C) and the temperature range of its liquid phase is narrow (approximately 20 °C).

Liquid hydrogen must be stored in cryogenic tanks, such as the one shown in Figure 17.

Figure 17. A cryogenic tank for the storage of liquid hydrogen.

4.1.2. Underground Storage

Large volumes of uncompressed hydrogen can be stored underground, for example in salt caverns or depleted gas fields. Natural gas (methane) storage in underground cavities is a widespread practice that has been done for decades.

Some advantages of storing hydrogen underground include low costs, high operational safety and good sealing capacity. However, this approach is naturally confined to geologically suitable areas with the appropriate geological prerequisites.

Locations where hydrogen is stored in salt caverns include Teesside (in the UK) and certain areas of Texas (in the United States). These are presented in Figure 18.

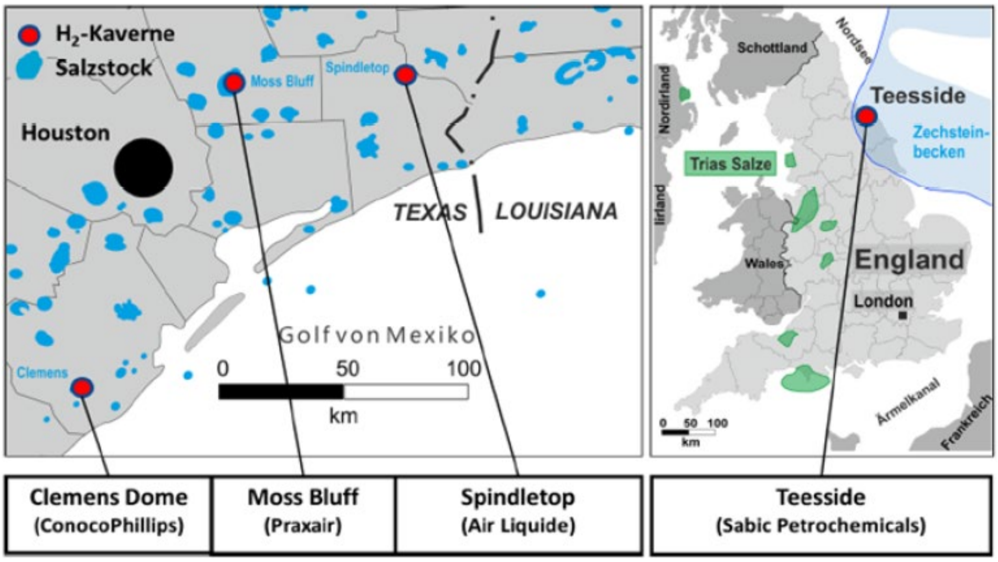


Figure 18. Storage of hydrogen in salt caverns in the US and the UK.
[Source: https://energnet.eu/wp-content/uploads/2021/02/3-Hevin-Underground-Storage-H2-in-Salt.pdf]

4.2. Hydrogen Distribution and Piping

Low and medium volumes of hydrogen can be transported via road transport, especially over shorter distances.

Compressed gaseous hydrogen may be transported by lorries called tube trailers, while liquid hydrogen may be transported by super-insulated, cryogenic tanker lorries called liquid tankers.

Figure 19. A tube trailer (left) and a liquid tanker (right).

For long-distance, high-volume transport, gaseous hydrogen can also be transported through pipelines – like natural gas is today. Generally, converting natural gas pipelines to carry a blend of natural gas and hydrogen (<15% H_2) may require modest modifications. However, converting these pipelines to deliver pure hydrogen may require more substantial modifications.

Hydrogen can be blended with fossil natural gas in many types of existing pipelines, augmenting it or, ultimately, replacing it altogether. Many grid injection projects exist around the world, including some in the UK: the H21 Leeds City Gate project presents a 100% hydrogen grid plan for the city of Leeds that is economically feasible and technically possible; while the HyDeploy project has realised the world's first hydrogen grid injection.

In 2020, the European Hydrogen Backbone (EHB) initiative presented its vision of a dedicated pan-European hydrogen infrastructure, shown in Figure 20.

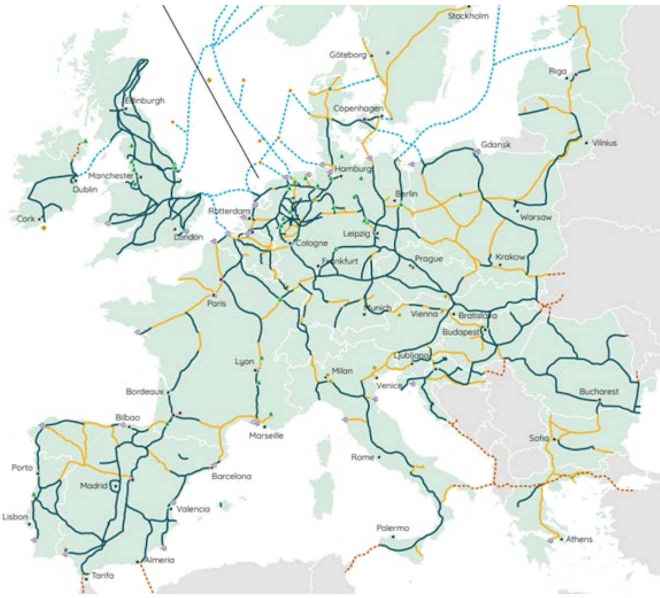


Figure 20. The proposed EHB infrastructure, highlighting new and repurposed pipelines.
[Source: https://gasforclimate2050.eu/wp-content/uploads/2022/04/EHB-A-European-hydrogen-infrastructure-vision-covering-28-countries.pdf]

Initially, the EHB infrastructure was planned to span across 10 European countries, based on repurposed existing natural gas pipelines as well as newly constructed hydrogen infrastructure. The vision was expanded to 28 countries in 2022, with a 53,000-km network proposed for 2040 at an estimated cost of €80-143 billion.

The initiative consists of a group of 31 gas infrastructure companies, with the latest project updates aiming to accelerate the implementation of the EHB in order to phase out Europe's dependence on fossil fuels from Russia.

4.3. Converting Hydrogen into Energy

One of the key strengths of hydrogen as an energy vector is the fact that the conversion between hydrogen and electricity is reversible, and both energy carriers can be considered complementary. When needed, hydrogen can be converted into electricity in two fundamental ways: electrochemically (in a fuel cell) or through combustion.

4.3.1. Fuel Cells

A fuel cell is an electrochemical cell that converts chemical energy into electricity. This happens through a reaction between hydrogen and oxygen.

They require a continuous source of hydrogen and oxygen (often from air). If green hydrogen is used, the electricity produced is clean – excess hydrogen and water vapour are the only by-products.

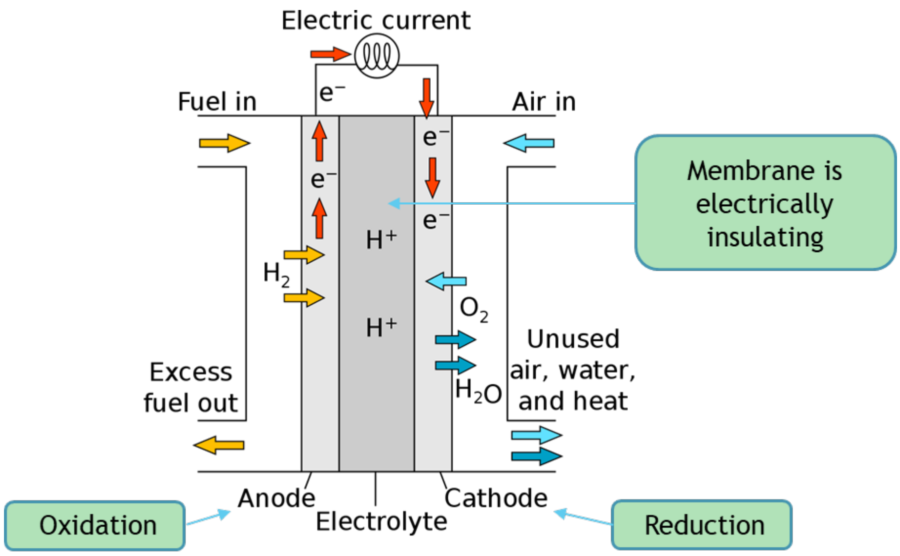


Figure 21. Schematic of a fuel cell.

Fuel cells have an anode, where the fuel (hydrogen) comes in; and a cathode, where oxygen is supplied. The two sides are separated by an electrically insulating membrane. Fuel cell operation is divided in four basic steps:

1. A catalyst causes hydrogen atoms dissociate into protons and electrons;

2. The protons travel through the membrane to the cathode;

3. The electrons are then forced to travel in an external circuit;

4. Power is then supplied.

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

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

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

Fuel cells are usually assembled into a stack, where the currents generated add up.

They have a wide range of applications: when coupled with an electric engine, they can power many means of transportation, such as cars, trains, buses, lorries, marine vessels and aeroplanes. They can also power devices such as personal electronics, torches, toys, drones, and even military applications; and backup power systems for off-grid applications such as task lighting, security cameras, environmental monitoring and process control systems.

Fuel cells have no major moving parts and don't involve combustion. Therefore, they are extremely reliable. However, parts are expensive (membranes, current collectors, etc.), high-purity hydrogen is still relatively expensive, and their assembly needs to be very precise to avoid leaks.

Lab Experiment → At this point a lab experiment is recommended so that learners can operate a small 1W fuel cell stack with five 200mW modular cells. The cells can be added or removed as needed. Instructions can be found at https://www.fuelcellstore.com/manuals/f108-f109-f110-fuel-cell-stacks.pdf

4.3.2. Hydrogen Combustion

Combustion is an exothermic chemical process in which a substance reacts with oxygen and gives off heat. In the combustion of hydrogen, it reacts with oxygen to form water, with the release of energy:

$$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (g) + \text{energy}$$

This reaction is commonly used in the space sector to power rocket engines.

Hydrogen does not produce carbon emissions after combustion. However, when burned in air, Nitrogen Oxides (NOx) are produced due to the Nitrogen that is present in atmospheric air.

Hydrogen burns with a pale blue flame that is nearly invisible in daylight – the flame may appear yellow if there are impurities in the air such as dust. A pure hydrogen flame will not produce smoke, and the flame temperature is relatively high.

Table 7. Comparison of the temperature of a hydrogen flame with those from other fuels.

Fuel	Flame Temperature in the air
Hydrogen	2,045 °C
Methane	1,957 °C
Propane	1,980 °C
Candle	1,000 °C

Additionally, hydrogen flames have low radiant heat – you may not feel any heat until you are very close to (or in) the flame. Thus, using flame detectors such as thermal imaging cameras is the best way to detect a hydrogen flame.

Applications for hydrogen combustion include:

- ✓ Hydrogen Internal Combustion Engines (ICEs): they are nearly identical to traditional spark-ignition engines, but use hydrogen as a fuel. Hydrogen ICEs tend to me most efficient under high loads, while fuel cells generally prove to be more efficient at lower loads.

- ✓ As an alternative to methane: hydrogen can be combusted and used for the same applications of fossil natural gas, including combustion in gas turbines, home heating and cooking, and industrial heating.

Discussion → An in-class discussion is recommended to highlight key differences between using hydrogen in fuel cells and in combustion, and to discuss the issue of NOx emissions in the combustion of hydrogen.

CONTINUOUS ASSESSMENT 4: PRODUCTION OF A FUEL CELL DIAGRAM

-------- End of Block 4 --------

-------- BLOCK 5 --------

5.1. Hydrogen in the Petrochemical Industry

Petroleum refineries and ammonia production currently dominate the world's demand for hydrogen, accounting for over 90% of total consumption. The problem is worsened by the fact that these fossil fuel related applications are typically serviced by captive, large-scale Steam Methane Reformer (SMR) plants.

In oil refineries, two processes involving hydrogen take place: hydrotreating and hydrocracking.

5.1.1. Hydrotreating

Hydrotreating – or catalytic hydrogen treating – removes objectionable materials from petroleum fractions by selectively reacting these materials with hydrogen. The process takes place in a reactor, at relatively high temperatures.

These objectionable materials include sulphur, nitrogen and aromatics, which are naturally contained in oil. The process upgrades the quality of atmospheric emissions of the resulting fuels by reducing their sulphur and organometallics level.

The growing demand for transportation fossil fuels in the 20th century, combined with the refining industry's efforts to meet the global trend for cleaner fuels, mean that hydrotreating has become an increasingly important refinery process.

Similarly, a process called hydrodesulphurisation can also be used to remove sulphur from natural gas, if required.

5.1.2. Hydrocracking

Hydrocracking is a process in which heavy oil is broken into lighter, more valuable products such as gasoline, kerosene and diesel. The process takes place at elevated temperatures and pressures, in the presence of a catalyst.

Hydrocracking consists of carbon-carbon bond breaking accompanied by hydrogenation. The process plays a key role in petroleum processing, providing high-value fuels and upgrading low-quality feedstock to make them suitable for further processing.

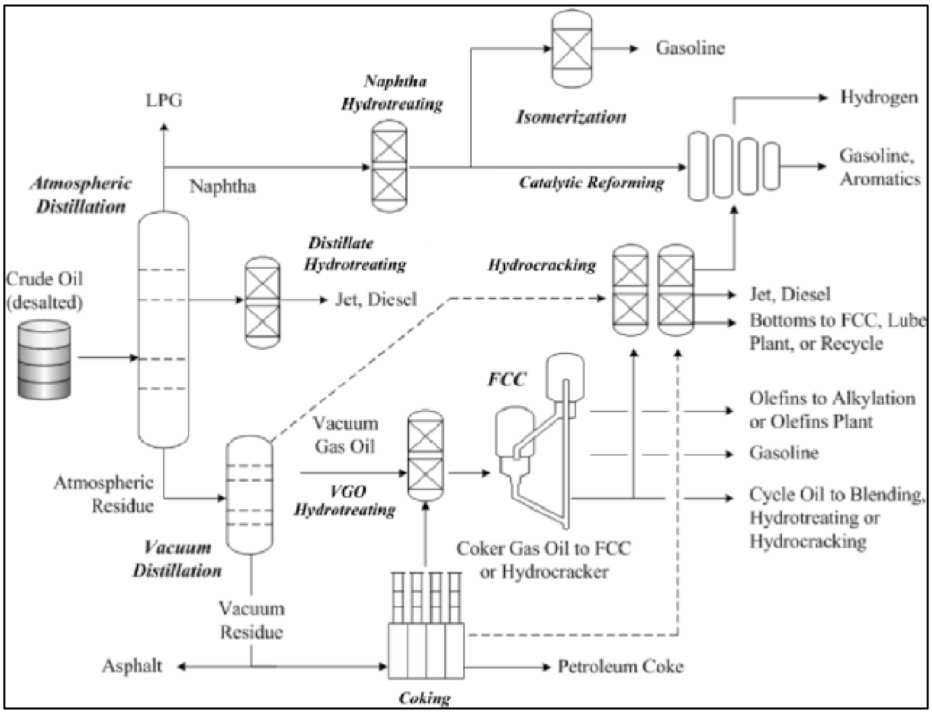


Figure 22. Hydrotreating and hydrocracking processes.
[Source: Robinson, Paul & Dolbear, Geoff. (2007). Hydrotreating and Hydrocracking: Fundamentals]

5.2. Ammonia Production

Today, around half of the world's hydrogen is used to produce ammonia (NH_3). This compound is the foundation for the nitrogen fertiliser industry which plays a key role in agriculture.

Ammonia itself is not a greenhouse gas – however, ammonia emissions need to be addressed. The oxidation of ammonia to nitrite by bacteria is responsible for global emissions of nitrous oxide (N_2O), also known as "laughing gas" – a potent GHG and a major cause of ozone depletion. Today, the vast majority of ammonia emissions comes from agricultural processes and practices.

For the production of ammonia, hydrogen is combined with nitrogen, according to the reaction:

$$N_2(g) + 3H_2(g) \xrightarrow[300-550^\circ C,\ 100-300\ \text{atm}]{\text{Haber Bosch catalyst}} 2NH_3(g)$$

This is called the Haber-Bosch process – a mature, low-cost process developed in the early 20th century by German chemist Fritz Haber and turned into an industrial process to make fertilisers by Carl Bosch.

5.2.1. Power-to-Ammonia

Ammonia production can also present a solution for the storage of hydrogen. The concept – named Power-to-Ammonia (P2A) – consists of producing green hydrogen via electrolysis and then converting it into ammonia.

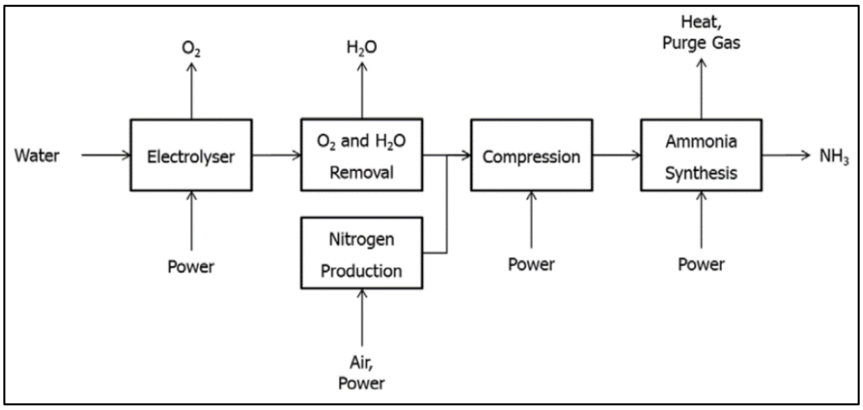


Figure 23. The Power-to-Ammonia concept.

A lot of the world’s hydrogen is currently used to produce ammonia, but not in a sustainable way such as P2A. The process presents several advantages:

- ✓ Ammonia has a high energy density, so transporting and storing it in large volumes is more feasible than just pure hydrogen;
- ✓ It can be transported and stored as a liquid;
- ✓ The chemical industry can use it as a renewable feedstock for the production of fertilisers and other products.

However, reducing of the carbon footprint of ammonia by producing it via electrolysis is only possible if the electricity used is renewable. In other words, P2A only presents an environmental advantage if it uses green hydrogen.

Figure 24 shows the Power-to-Ammonia concept in the context of “Power-to-X” – the conversion of hydrogen into different fuels.

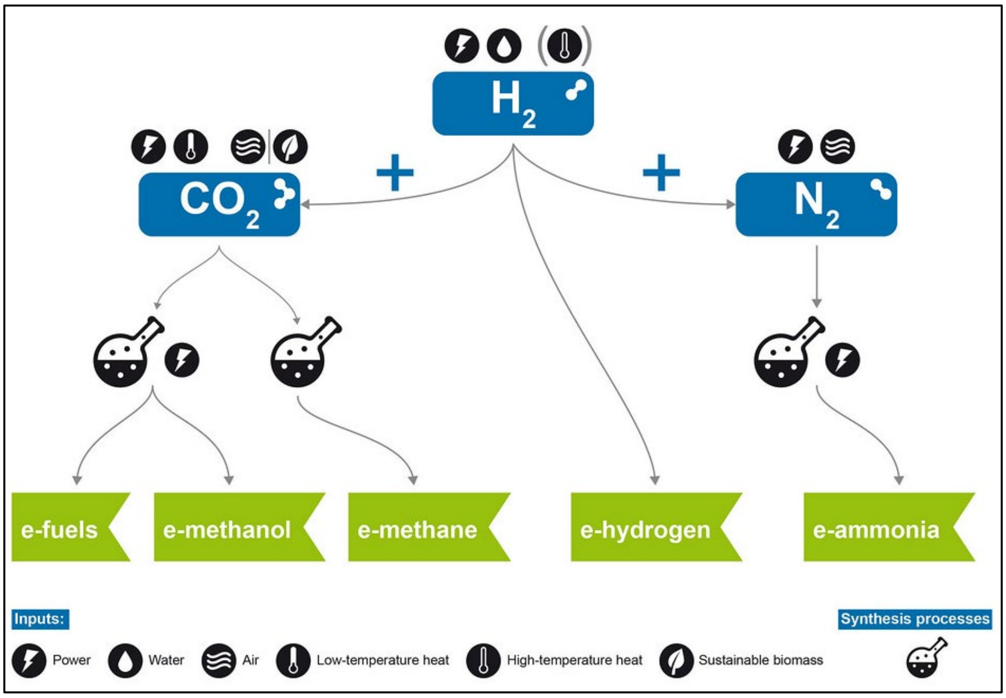


Figure 25. Overview of inputs, processes and Power-to-X products [Source: Oeko-Institut].

Discussion → An in-class discussion is recommended to identify how the current scenario of hydrogen in the petrochemical industry could be more sustainable.

5.3. Hydrogenation

Hydrogenation is a process that uses hydrogen to saturate organic compounds. It consists of adding pairs of hydrogen atoms to molecules which – in the presence of a catalyst such as platinum or nickel – reduce double and triple bonds into single bonds.

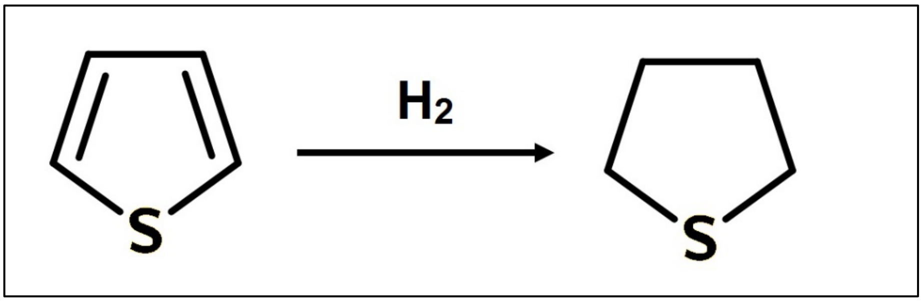


Figure 26. Hydrogenation.

Hydrogenation generates, for example, saturated fat. The example below shows the saturation of an organic molecule using platinum as catalyst, in which the double bond is reduced.

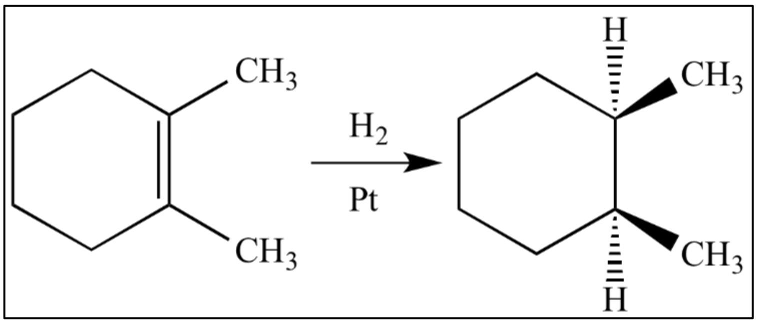


Figure 27. Example of hydrogenation using platinum.

The food industry performs hydrogenation extensively when processing vegetable oils: changing the degree of saturation of some fats can change some important physical properties (such as their melting point) making liquid oils become semi-solid. Margarine is a well-known product of hydrogenation – in fact, over 7 kg of hydrogen are needed to produce a tonne of margarine.

The process is also performed in the chemical and pharmaceutical industries. In these cases, hydrogenation is used to modify molecules and provide various organic compounds to support the production of different products and medicines.

5.4. Other Roles for Hydrogen in Industry

Today, besides the petrochemical industry and hydrogenation processes, hydrogen is also used as a feedstock by a variety of industries, such as:

5.4.1. Semiconductor Manufacturing

Semiconductor chips are electric circuits with many components, and are an integral part of computer processors, memory chips and micro-controllers. Semiconductor manufacturers, such as Intel, Analog Devices, Samsung and Toshiba, employ hydrogen in various steps of their fabrication processes.

These processes include mainly:

- Lithography → A process used in microfabrication to transfer geometric patterns to a surface. In lithography, hydrogen acts as a cleaning or shielding gas.

- Thin-film deposition → The technology of applying a very thin film of material onto a surface or another deposited coating. In thin-film deposition, hydrogen acts as a carrier gas, transporting the deposition materials into a vacuum chamber where the deposition takes place. Argon can also be used, although hydrogen produces better results.

5.4.2. Hydrogen as a Coolant

Hydrogen is an excellent coolant, and it is often used to enhance heat transfer for cooling turbine power generators, especially in high-capacity generators (larger than 100 MW). In fact, hydrogen gas is seven times more effective as a heat transfer medium than air and 14 times less dense.

However, most power plants rely on the delivery of hydrogen to cool their generators instead of producing it on-site. This inevitably causes safety risks and inefficiencies, as well as inconveniences and costs associated with refilling, transporting and storing hydrogen tanks.

Case Study → Hydrogen Generator Improves Efficiency and Safety at Puerto Rico's Aguirre Power Plant – swapping storage tanks for an electrolysis facility. https://www.azom.com/article.aspx?ArticleID=10539

5.4.3. Backup Power

Hydrogen can be used as a power source in backup power systems and generators. Such systems are employed for off-grid applications such as:

- ✓ Task lighting;
- ✓ Security cameras;
- ✓ Environmental monitoring;
- ✓ Process control systems.

For instance, chemical company Linde commercialises the HYMERA system (Figure 28), labelled the world's first "commercially viable" hydrogen fuel cell generator. The system can provide up to 175 W of peak power and offers an alternative to fossil-based generators and bulky battery banks.

Figure 28. The HYMERA generator [Source: Linde].

5.4.4. The Glass and Metal Sectors

The glass industry uses hydrogen in combination with nitrogen as a protective atmosphere to prevent oxidation and improve glass quality.

In turn, the metal/steel industry uses hydrogen for applications such as:

- ✓ Controlled atmospheres;
- ✓ In the heat treatment of non-ferrous metals;
- ✓ To support plasma welding and cutting.

5.4.5. Aerospace Applications

The aerospace industry uses hydrogen as a fuel gas for spacecraft or in some of their internal systems. In combination with an oxidiser (such as liquid oxygen), liquid hydrogen yields the highest specific impulse of any known rocket propellant.

Nowadays, liquid hydrogen is the fuel of choice of space programmes and satellite launches.

Guest Speakers → At this stage, industry representatives can bring value and add a fresh perspective to the course by sharing their real-world experiences.

CONTINUOUS ASSESSMENT 5:
SCENARIO STUDY

-------- End of Block 5 --------

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Figures and tables are referenced in caption when applicable.