SCRREEN2

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FACTSHEETS UPDATES

HYDROGEN

AUTHOR(S):

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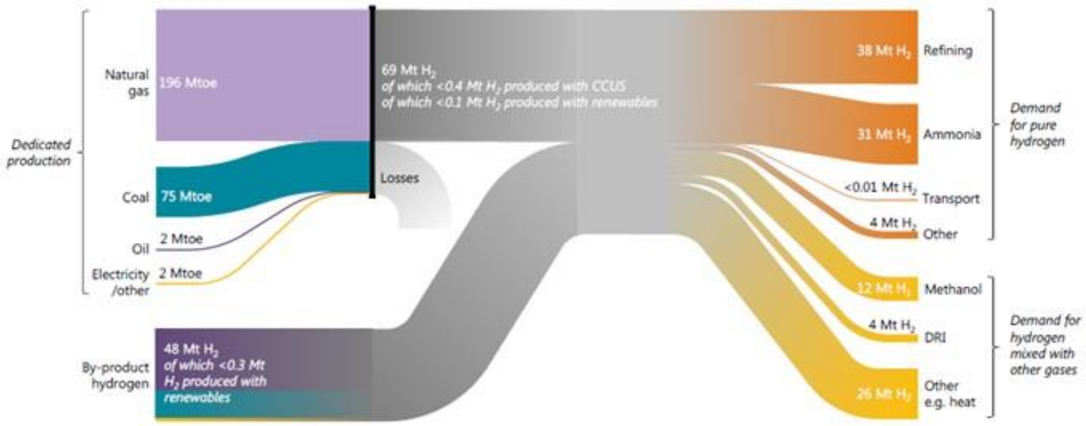
HYDROGEN

OVERVIEW

Hydrogen is the most abundant and lightest of the elements; it is odourless and non-toxic. It has the highest energy content of common fuels by weight - nearly three times that of gasoline. Hydrogen is not found free in nature and must be "extracted" from diverse sources: fossil energy, renewable energy, nuclear energy and the electrolysis of water. A separate energy source (electricity, heat or light) is required to "produce" (extract or reform) the hydrogen.



Notes: Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. Other forms of demand for hydrogen mixed with other gases (e.g. carbon monoxide) include the generation of heat from steel works arising gases and by-product gases from steam crackers. The shares of hydrogen production based on renewables are calculated using the share of renewable electricity in global electricity generation. The share of dedicated hydrogen produced with CCUS is estimated based on existing installations with permanent geological storage, assuming an 85% utilisation rate. Several estimates are made as to the shares of by-products and dedicated generation in various end uses, while input energy for by-product production is assumed equal to energy content of hydrogen produced without further allocation. All figures shown are estimates for 2018. The thickness of the lines in the Sankey diagram are sized according to energy contents of the flows depicted.

Source: IEA 2019.

Figure 1: Hydrogen value chain globally (IEA, 2019)

Table 1. Hydrogen supply and demand in metric tonnes at the processing stage, 2020

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
90 million tonnes (IEA 2020)		1.1 Million tonnes	1.2%	EU27 99.88%	0% at the processing stage but based on natural gas imports

Price: the production cost of grey and blue hydrogen is influenced by the fuel cost as well as capital and operational expenses. However, technological improvement and the price reduction of renewable energies (that are used for green hydrogen) are expected to have a significant contribution in reducing hydrogen cost in the upcoming years (IRENA, 2018, 2019; Waikar, 2020).

Primary supply: Hydrogen is mainly industrially produced through four practices including (Press et al. 2008; Element Energy Ltd, 2018): steam methane (natural gas) reforming, gasification (of various feedstocks) partial

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oxidation of hydrocarbons, water electrolysis. Methane reforming, gasification and partial oxidation are the dominant technologies in terms of produced hydrogen amounts with a 48%, 18% and 30% share, respectively.

Secondary supply: Hydrogen is typically vented during industrial processes in the same stream as other waste gas components. The waste hydrogen gas has typically not been recovered for reuse. This is especially true in smaller scale applications, because there is no economical means by which to scrub the gas stream of accumulated impurities, or to compress it in a way that it could be efficiently stored for later use.

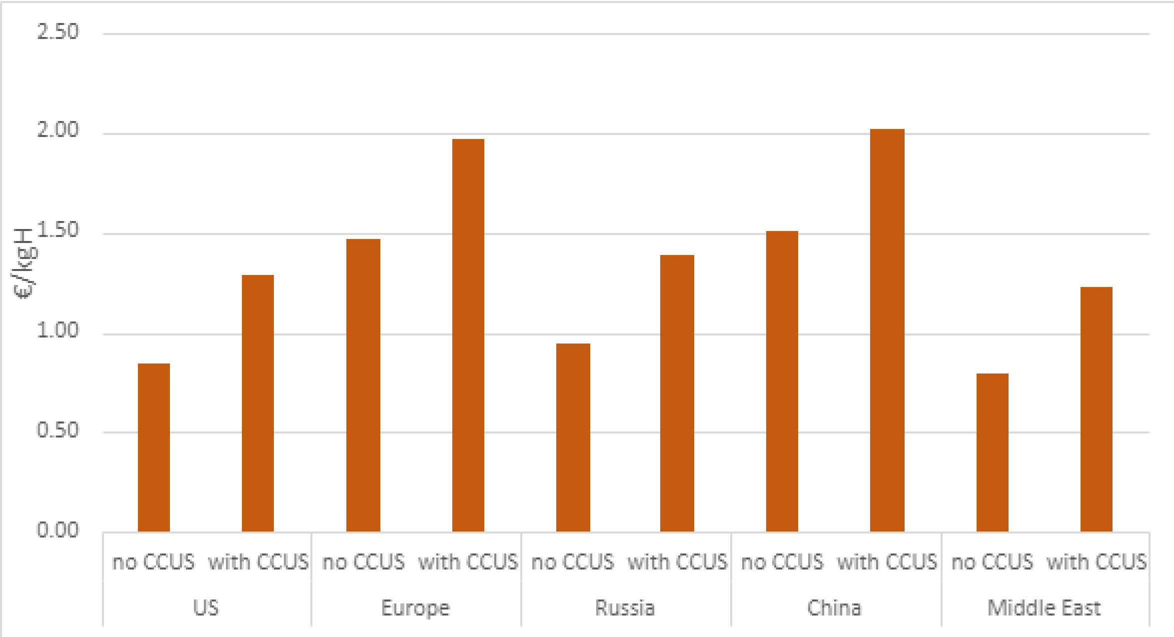

Figure 2. Hydrogen production cost using natural gas with and without carbon capture utilization and storage (CCUS) across different regions in 2018 (based on IEA, 2019)

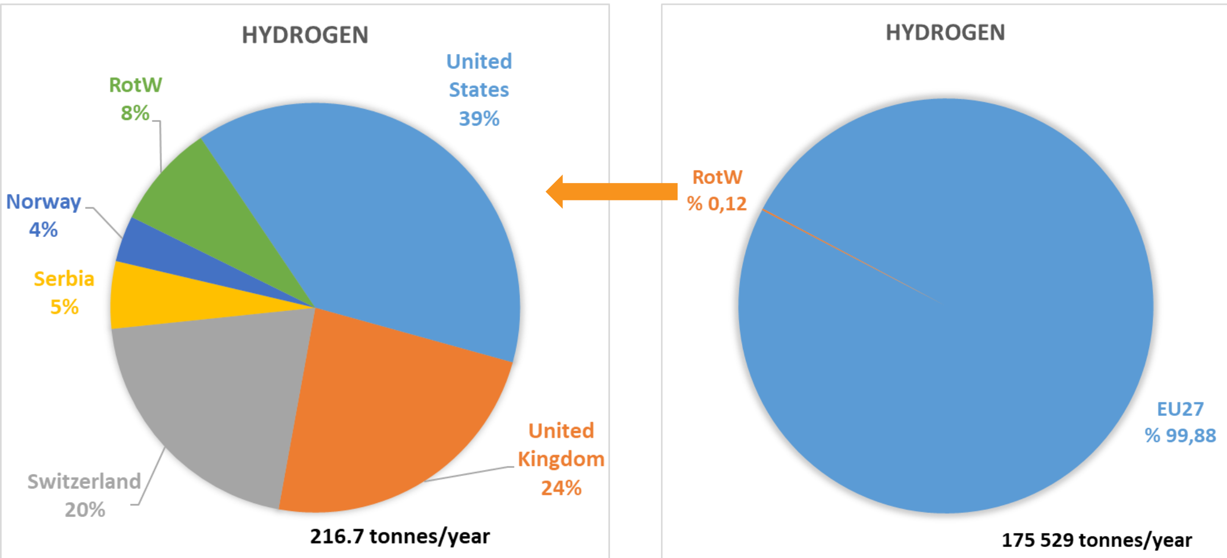

Figure 3 .EU sourcing of hydrogen (Eurostat 2022); average 2016-2020

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Use: The use of hydrogen in Europe is concentrated in three key areas: chemical secto(of which the majority is for ammonia production), refineries and metal processing. According to the report by Certify (2015) which uses data from internal sources and information from Linde in 2013, information is provided on the use of hydrogen across these sectors. Data from Petrochemicals Europe (2021) provides information drawn from a number of sources to estimate the use of hydrogen in Europe currently.

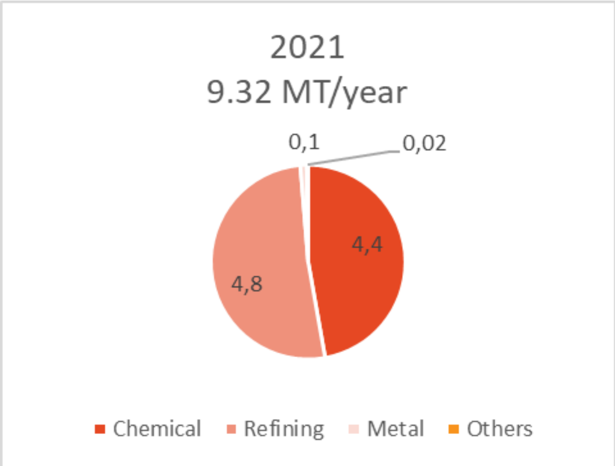

Figure 4. End use of hydrogen in Europe

Substitution: Hydrogen cannot be substituted in the various industrial applications neither in fuel cells requiring hydrogen as a fuel.

Other issues: Hydrogen production is mainly done from fossil fuels (i.e. steam reforming of natural gas, coal gasification and partial oxidation of methane) (Holladay et al. 2009; Liu, Song, and Subramani 2009).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 2. Hydrogen supply and demand in metric tonnes at the processing stage, 2020

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
90 million tonnes (IEA 2020)		1.1 Million tonnes	1.2%	EU27 99.88%	0% at the processing stage but based on natural gas imports

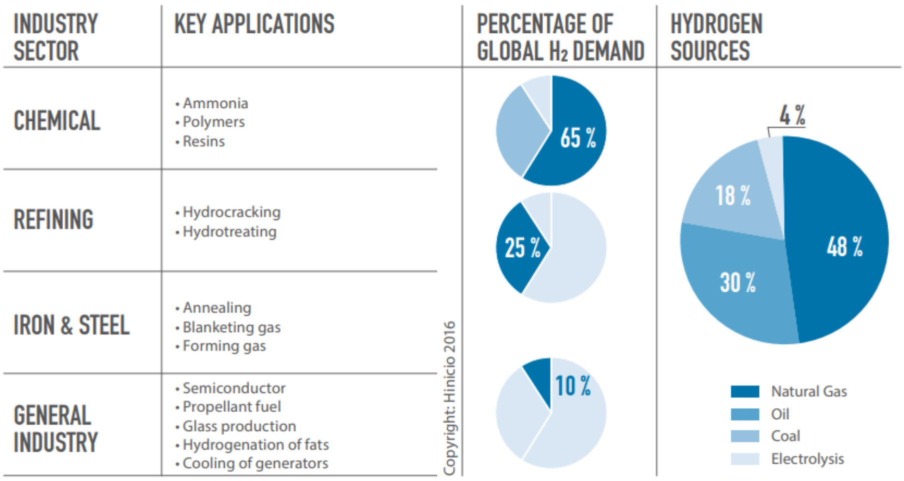

Figure 5. Global hydrogen demand and production sources (Source: IRENA, 2018)

Based on what source is used to produce hydrogen, the market can be segmented into "brown/black hydrogen", "grey hydrogen", "blue hydrogen" and "green hydrogen". "Brown or black" hydrogen refers to hydrogen production by transforming coal into gas. At high temperature (>700 °C), the gasification process converts coal into carbon monoxide, hydrogen, and carbon dioxide, with a controlled amount of oxygen and/or steam. The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas shift reaction. This hydrogen produced is known as brown or black depending of the type of coal used: brown (lignite) or black (bituminous) coal. It is the result of a highly polluting process since both CO_2 and carbon monoxide cannot be reused and are released in the atmosphere (Energy Cities, 2020). "Grey Hydrogen" is derived from natural gas through SMR. SMR mixes natural gas with very hot steam in the presence of a catalyst, where a chemical reaction creates hydrogen and carbon monoxide. Additional water is added to the mixture, converting the carbon monoxide to carbon dioxide and creating more hydrogen. "Blue hydrogen" is also derived from natural gas through SMR, but the carbon dioxide emissions produced are then captured and stored underground using the carbon capture, utilisation, and storage (CCUS) technology, leaving nearly pure hydrogen (Markets&Markets, 2021). Electrolysis of water produces "green hydrogen" from renewable energy resources. Green hydrogen has numerous applications, ranging from industrial

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feedstock to fuel cell vehicles and energy storage. The concept of green hydrogen is still in its early phase, and the renewable hydrogen production pathways span across a range of maturity levels (IRENA, 2018).

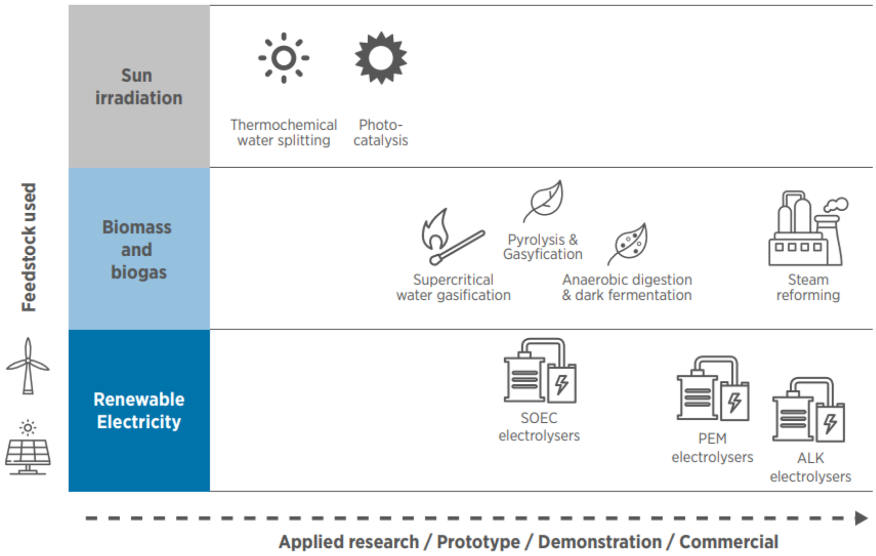

Figure 6. Renewable hydrogen production pathways and current levels of maturity (Source: IRENA, 2018)

The Asia-Pacific region will continue to lead hydrogen demand. Regarding black/brown, grey and blue hydrogen, refinery hydrogen by-product covers however only a third of hydrogen requirements, with the gap filled by dedicated on-site production and commercial supply. Most dedicated onsite production uses natural gas feedstock, but light fractions of oil distillation and heavier feedstocks – petroleum coke, vacuum residues and coal – are also used in some regions. Use of heavier feedstocks is mostly restricted to India and China, where gas needs to be imported. Coal gasification is routinely included in new refinery setups in China as a main or auxiliary hydrogen production unit.

Today, much of the refining and chemicals production that uses hydrogen based on fossil fuels is already concentrated in coastal industrial zones around the world, such as the North Sea in Europe, the Gulf Coast in North America and Southeast China (IEA, 2019). Market supply of hydrogen is an option in densely industrialised areas where developed hydrogen pipeline infrastructure exists, such as the US Gulf Coast and Europe's Amsterdam Rotterdam-Antwerp hub. As with dedicated on-site production, commercially available hydrogen is mostly produced from natural gas. The amount not coming from natural gas is generated through chemical processes: a by-product of operations such as steam cracking and chlorine production. In regions such as the US Gulf Coast, the commercialised hydrogen can meet over a third of total hydrogen demand.

In general, environmental regulations implemented in most industrialised countries result in increased hydrogen requirements at refineries for gasoline and diesel desulfurisation because of increased demand for cleaner fuels and tighter engine manufacturer specifications. Ongoing oil sands processing, gas-to-liquids, and coal gasification projects all require enormous amounts of hydrogen and were expected to boost the size of the market significantly until 2025. Alberta, Canada has an enormous area containing oil sands that can be processed to produce oil. This area is estimated to be the second-largest oil reserve after Saudi Arabia. Desulfurisation operations for these sands would consume vast quantities of hydrogen. Hydrogen is also

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driven by the manufacture of methanol. Substantial methanol consumption in direct-fuel use as motor gasoline is expected in countries such as China, Russia, South Africa, Venezuela, and several Middle Eastern countries.

Fuel cell power generation applications are expected to drive the demand for hydrogen and Asia Pacific is one of the leading markets for adopting green technologies to meet the government targets for reducing GHG emissions (Markets&Markets, 2021). Japan and South Korea are heavily investing in fuel cell adoption since 2009 because of the commercial deployment of Japanese fuel cell micro-CHP products. Japan is the first nation to commercialise fuel cells and is supporting the projects related to the use of fuel cells in residential and automotive applications. Singapore, India, and Malaysia are also showing interest and have just started or are expected to start exclusive programs to promote fuel cells in regional markets. These countries are initially focusing on backup power (stationary application) fuel cells.

It is worth noting thar hydrogen cannot be substituted in the various industrial applications neither in fuel cells requiring hydrogen as a fuel.

OUTLOOK FOR SUPPLY AND DEMAND

Markets and Markets project that the global hydrogen generation market would reach USD 201 billion by 2025, at a CAGR of 9.2% during the 2020-2025 forecast period, with the market growth being driven by increased fuel cell power generation application (Markets&Markets, 2021).

Pre-COVID-19, the Future of Hydrogen report from the IEA forecasted that the demand for hydrogen in 2030 would increase by 7 % in oil refining sector, around 30 % in the chemical sector and would double in the steel production sector, which accounts for around 30 % increase of the overall hydrogen demand (IEA, 2019). Higher demand was foreseen according to the European Roadmap for hydrogen for the same timeframe: an increase between 48 % and 105 % in case of 'Business as usual' and 'Ambitious' scenario, respectively. An increase between 140 % and almost 600 % was anticipated by 2050 with respect to the same scenarios (FCH, 2019). The consumption of hydrogen for Industry, Transport, Residential & services and Power sector (storage) in 2050 would be expected to increase by 5 Mtoe (2 % increase as of today) according to a 'Baseline' scenario. In a high hydrogen deployment scenario, the consumption of hydrogen was projected to increase by 145 Mtoe for the same year, representing 44 % increase as of today (EC, 2018).

In 2021 however, the IEA predicts that the COVID-19 crisis will have significant impacts on hydrogen technologies because the oil refining, the chemical sector and steel manufacturing sectors, have all been highly impacted by the Covid-19 outbreak (IEA, 2019). The IEA forecasts lower gasoline (-9%), diesel (-6%) and jet fuel (-26%) consumption in 2020, while demand for key chemicals produced using hydrogen (e.g. methanol) has dropped 7%. Although hydrogen fuel-cell vehicle sales had accelerated impressively in 2019, and the early 2020s were expected to be record years for the deployment of electrolyser capacity, the IEA suspects that these trends may now be at risk due to slackening demonstration of key end-use technologies and delayed (or even cancelled) low-carbon production projects.

Several countries are moving towards a green hydrogen economy and companies' investments are worth following to understand the future trends: Australia as a hydrogen-based low-emission fuel, Canada with fuel

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cells, China and France with hydrogen vehicles, Germany investing in R&D, Japan in transport and South Korea in hydrogen storage (Deign, 2019).

Future developments in policy and regulation will be instrumental in shaping the future of hydrogen.

EU TRADE

For the purpose of this assessment, hydrogen is evaluated at the processing stage.

Table 3. Relevant Eurostat CN trade codes for hydrogen

Processing/refining	
CN trade code	**title**
28041000	Hydrogen

Figure 7 shows the EU trade in hydrogen (in tonnes) between 2000 and 2021. The EU was a net exporter of hydrogen. The imports of hydrogen varied from 87 t in 2020 to 562 t in 2018, while hydrogen exports ranged between 245 t in 2001 and 2087 t in 2000.

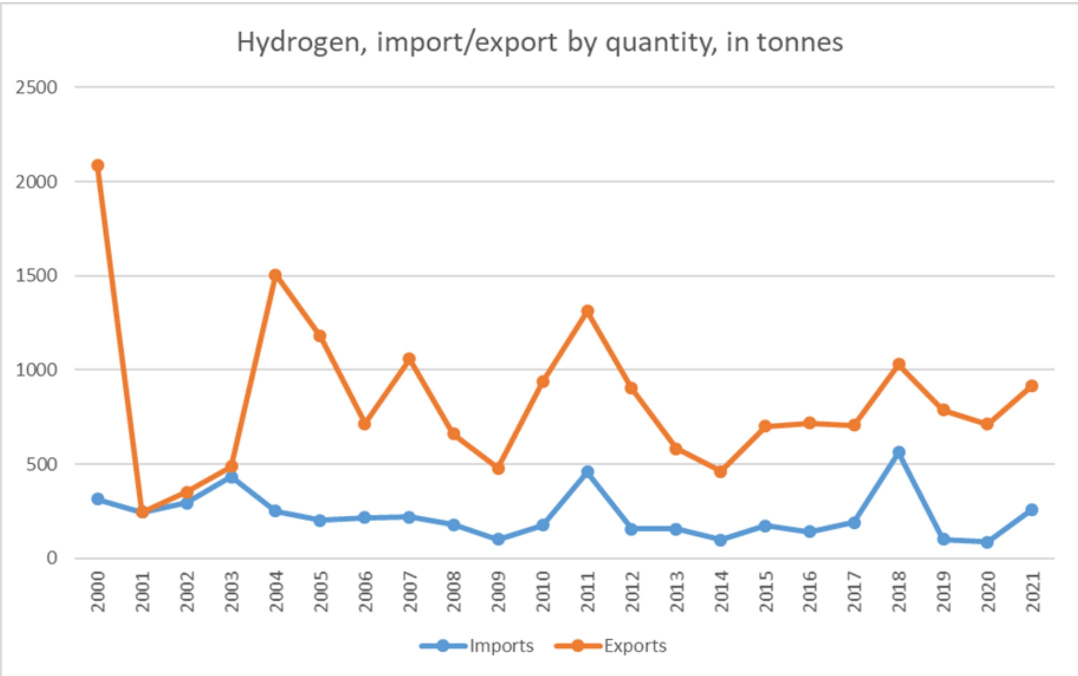

Figure 7. EU trade flows of hydrogen (CN 28041000) from 2000 to 2021 (based on Eurostat, 2021)

Figure 4 presents the average EU imports of hydrogen by country for the period 2000-2020. The major EU supplier of hydrogen was Switzerland, covering 42% of EU's hydrogen imports in the period. United Kingdom, United States, Norway and Serbia followed with 30%, 12%, 5% and 4% of EU's total hydrogen imports, respectively. The supply structure has changed over the period significantly: while Switzerland was, by far, the main supplier of hydrogen to the EU in the 2000s, UK has the largest share in EU's hydrogen imports in the 2010s.

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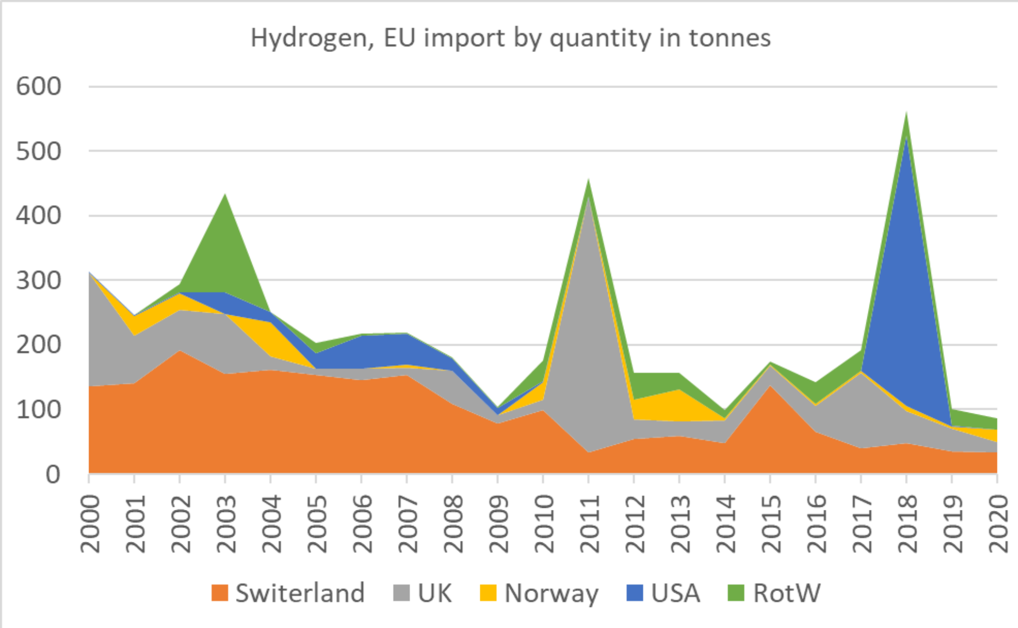

Figure 8. EU imports of hydrogen by country between 2000 and 2020 (based on Eurostat, 2021).

PRICE AND PRICE VOLATILITY

As shown above, the production cost of grey and blue hydrogen is influenced by the fuel cost as well as capital and operational expenses. However, technological improvement and the price reduction of renewable energies (that are used for green hydrogen) are expected to have a significant contribution for reducing hydrogen cost in the upcoming years (IRENA, 2018, 2019; Waikar, 2020). In fact, some experts suggest that green hydrogen will become cost-competitive by 2030 with hydrogen prices of US $ 1.4/kgH, reaching US $ 0.8/kgH in 2050 for some regions (Collins, 2020; Waikar, 2020).

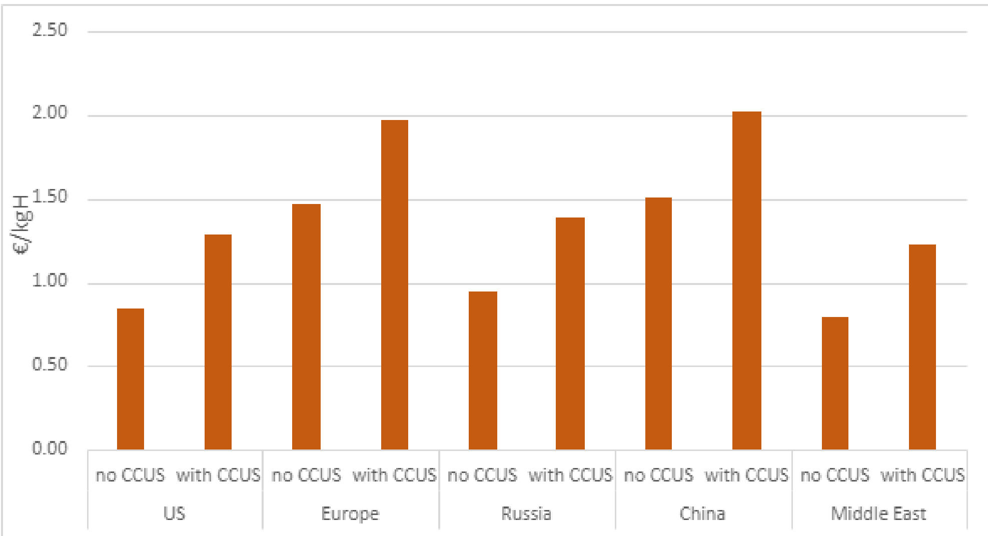

Figure 9. Hydrogen production cost using natural gas with and without carbon capture utilization and storage (CCUS) across different regions in 2018 (based on IEA, 2019)

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DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Global demand of hydrogen reached 94 million tonnes in 2021 (IEA, 2022). The demand for hydrogen in the refinery sector based on global oil refining capacity is shown in **Erreur ! Source du renvoi introuvable.** (BP, 2018).

On average Europe requires around 15 % of the hydrogen globally for the considered sectors.

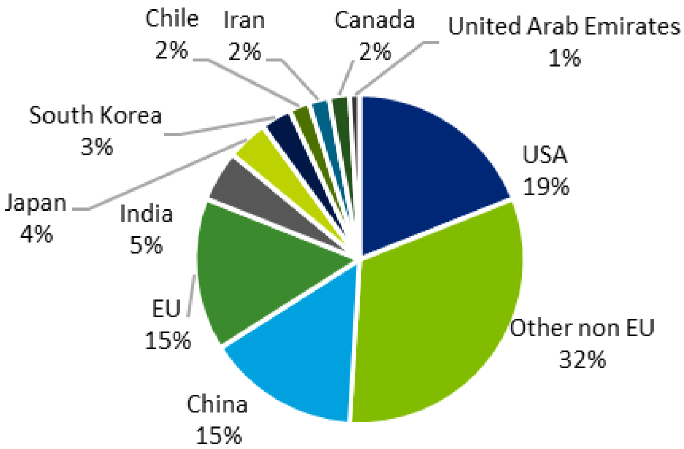

Figure 10 Hydrogen demand for refining (BP, 2018)

Hydrogen processing stage EU consumption is presented by HS code CN 28041000 hydrogen. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2021) for hydrogen using PRCCODE 20111150.

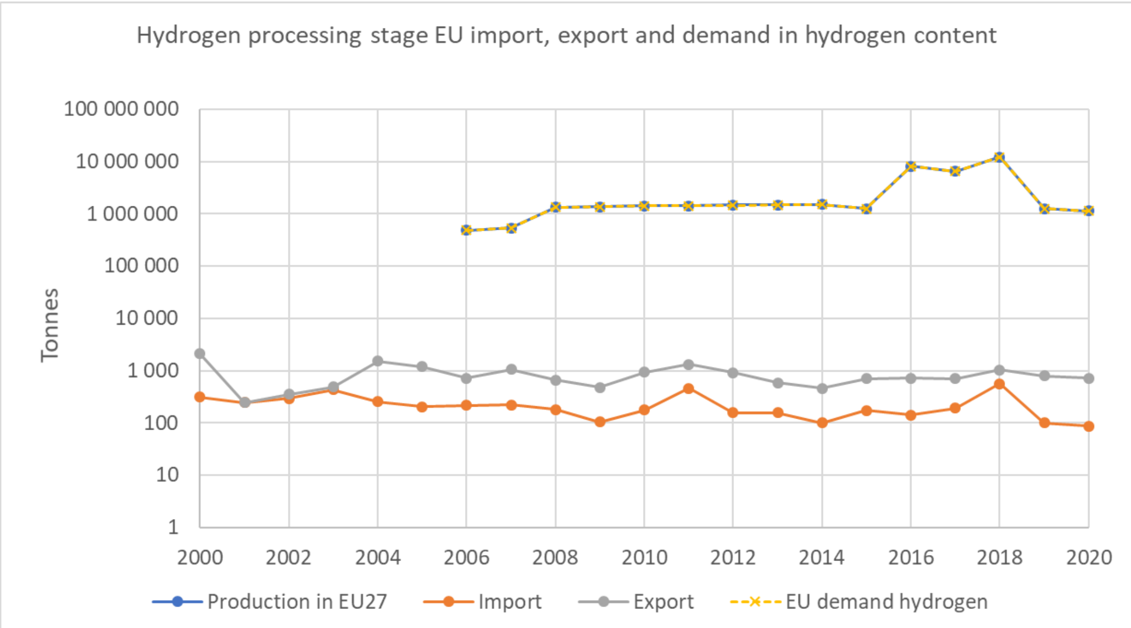

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Figure 11. Hydrogen (CN 28041000) apparent EU consumption (EU production+import-export).

In terms of produced hydrogen, EU is self-sufficient, however, it has to be noticed that hydrogen is mainly produced by gaz vaporeformage, coal gasification or fuel oxidation, for which the EU is highly dependent. Therefore, the import reliance should be built on the import reliance on gas, oil and coal, according to the related share in the hydrogen production.

EU USES AND END-USES

The use of hydrogen is Europe is concentrated in three key areas: chemical sector, of which the majority is for ammonia production; refineries; and metal processing.

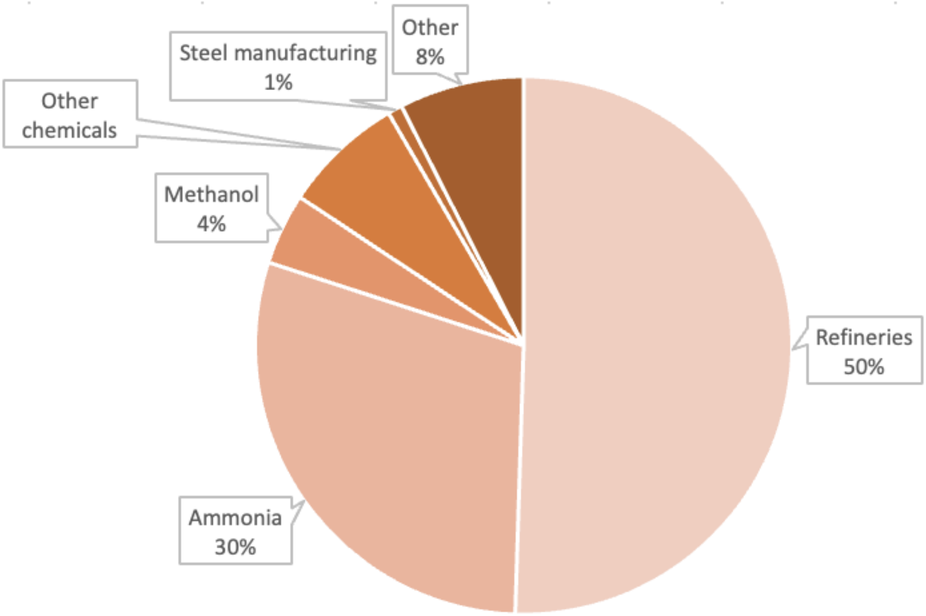

Figure 12. End use of hydrogen in Europe (EU27; Hydrogen Europe, 2021).

In Europe in 2018 around 3.8 million tonnes hydrogen per year are required for ammonia production and only 0.35 million tonnes hydrogen per year for methanol production (IEA, 2019). A typical ammonia plant has the capacity to produce between 1,000 and 2,000 tonnes per day of this product, needing a hydrogen feedstock to operate ranging from 57,500 to 115,000 tonnes per year (CertifHy, 2015). The ammonia market in Europe is driven by the biggest fertilizer supplier: Yara. The global ammonia market is expected to be relatively stable with an annum rate growth of 0.1%. Methanol is the second largest hydrogen consumer in the chemical sector in Europe. Since it is a mature market, it is forecasted that it will maintain a stagnant growth.

The hydrogen volume consumption of a refinery site depends strongly on the processes involved and products generated. Therefore, it may change greatly from refinery to refinery and cannot be calculated from the production volumes alone. In general terms, a typical plant operates with hydrogen production capacities in a range of 7,200 to 108,800 tonnes per year, and up to 288,000 tonnes per year for new and complex large scale refineries.

The main actors in the European market are BP, Total, Shell and EXXON (the latter with a small participation).

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Metal processing encompasses the use of hydrogen to yield iron reduction. The market share for the metal processing industry is 6% (410,000 tonnes). The typical hydrogen consumption in this type of plant is rounded between 36 to 720 tonnes per year (CertifHy, 2015). The activity in the metal processing sector has decreased (around 2.7% per year) since 2009 as a result of the financial crisis.

The value added by each sector with time is given below (the other sector is not provided as this too small and also represents a wide range of sectors).

Table 4. Hydrogen applications, 2-digit NACE sectors and value added per sector for 2019 (Eurostat, 2022). * to end of 2014 only.

Applications	NACE 2-digit sector	Value added (M€)
Chemical sector	C20 - Manufacture of chemicals and chemical products	117,150*
Refineries	C19 - Manufacture of coke and refined petroleum products	24,896
Metal processing	C24 - Manufacture of basic metals	63,700
Others	C32 - Other manufacturing	64,757* (inc C31)

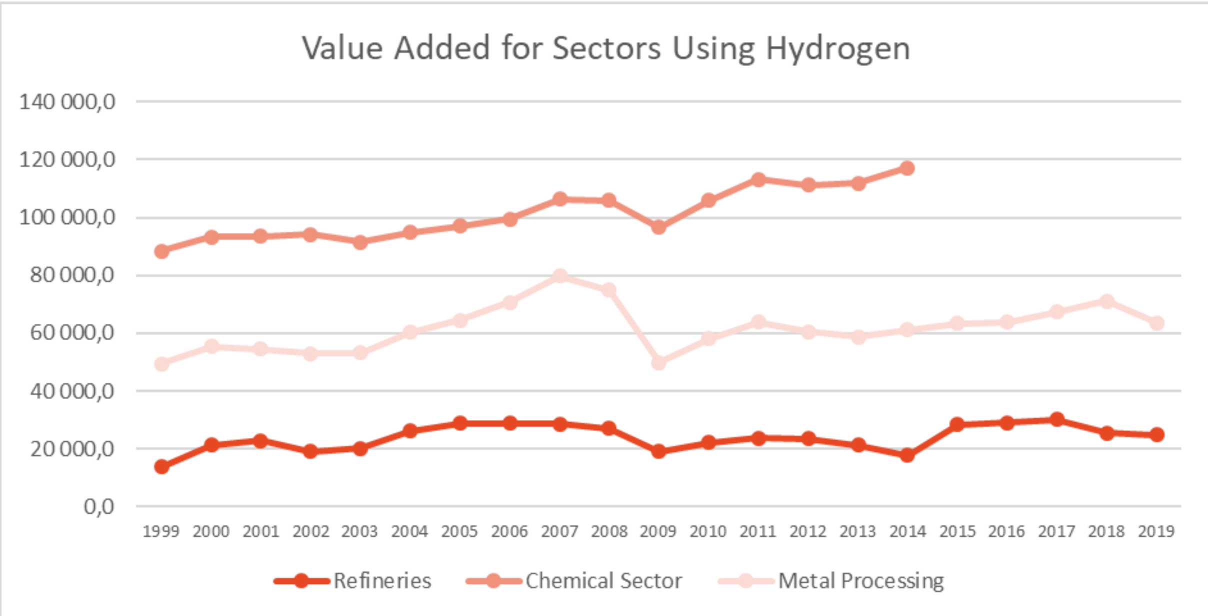

Figure 13. Value added per 2-digit NACE sector over time (Eurostat, 2021)

SUBSTITUTION

Hydrogen cannot be substituted in the various industrial applications neither in fuel cells requiring hydrogen as a fuel. Raw materials involved in technologies for hydrogen production are:

- PGMs (Pt, Pd, Rh, Ru)
- Titanium

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- Natural Graphite
- Rare Earths Elements
- Cobalt
- Borates

The most important raw materials identified as vulnerable are Iridium, Palladium, Platinum, Ruthenium, Rhodium, Titanium

The options for substitution for these are covered in other CRM Factsheet sections, specific to each material.

SUPPLY

EU SUPPLY CHAIN

According to 2019-year data, European Union (EU) currently uses approximately 8.4 million tonnes (Mt) of hydrogen annually (FCHO, 2022). The hydrogen production capacity in EU can be seen in **Erreur ! Source du renvoi introuvable.**.

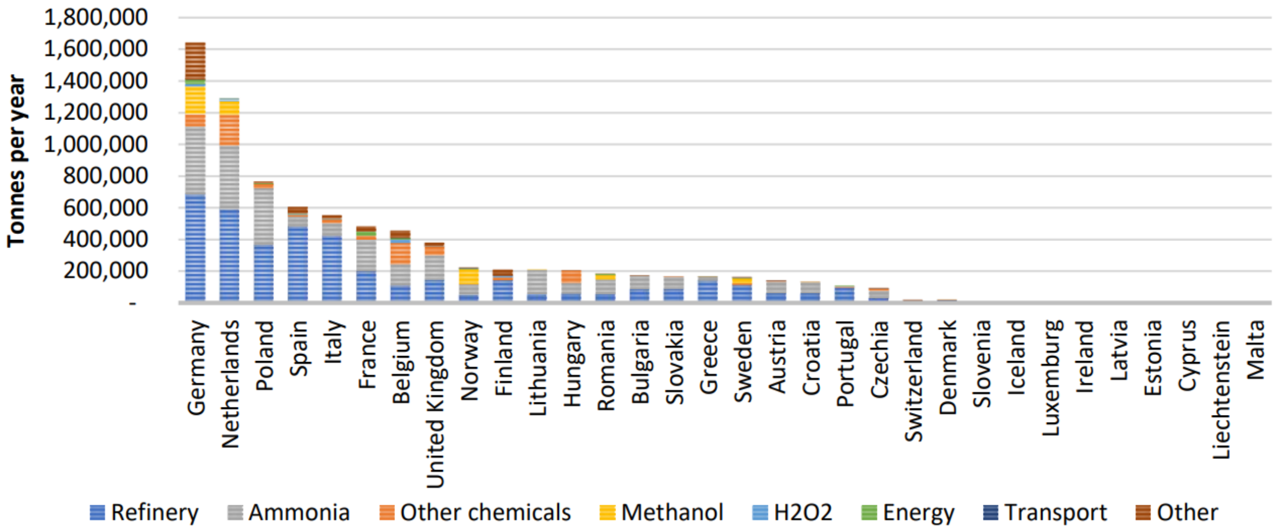

Figure 14. Total hydrogen production capacity, as captive, merchant and by-product, by country in EU (FCHO, 2022).

A small amount of hydrogen produced in EU is exported inside EU and to non-EU countries. In 2019 the total amount of hydrogen exported by EU countries both to other EU member states and externally, reached 107 thousand tonnes, which represent >1.5 % of total hydrogen consumption. Most of this trade is taking place within the EU, with only 1,000 – 2,000 tonnes per year exported to countries outside the EU (Hydrogen Europe Monitor, 2020).

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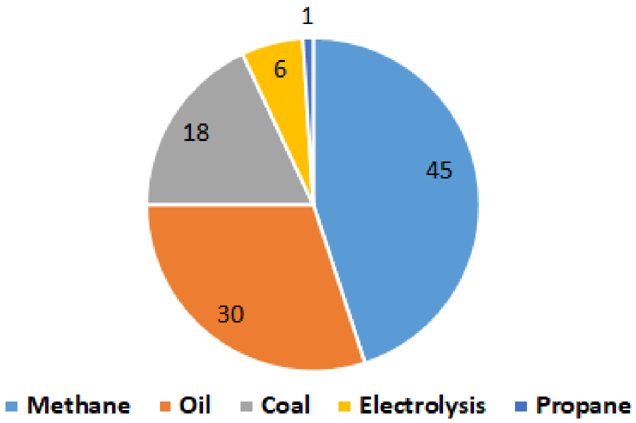

Figure 15 .H_2 production sources (amount %) in Europe. http://458energy.com/index.php/en/about-hydrogen

The progressive sustainable development of the hydrogen supply chain to end consumers comprises three additional stages (**Erreur ! Source du renvoi introuvable.**): (a) the construction of new hydrogen production facilities of multimegawatt capacities for large consumers (medium-sized to large industry, various means of transport such as: hydrogen trains, boat and bus fleets), (b) the expansion of new hydrogen facilities as "semi-centralised" or "centralised" hydrogen sources supplying smaller local consumers and (c) the hydrogen supply to end applications (mass market) which will lead to the existence of regions with surplus of hydrogen, therefore there will be a possibility of exporting between different regions or even intercontinental hydrogen market between countries (IRENA, 2018).

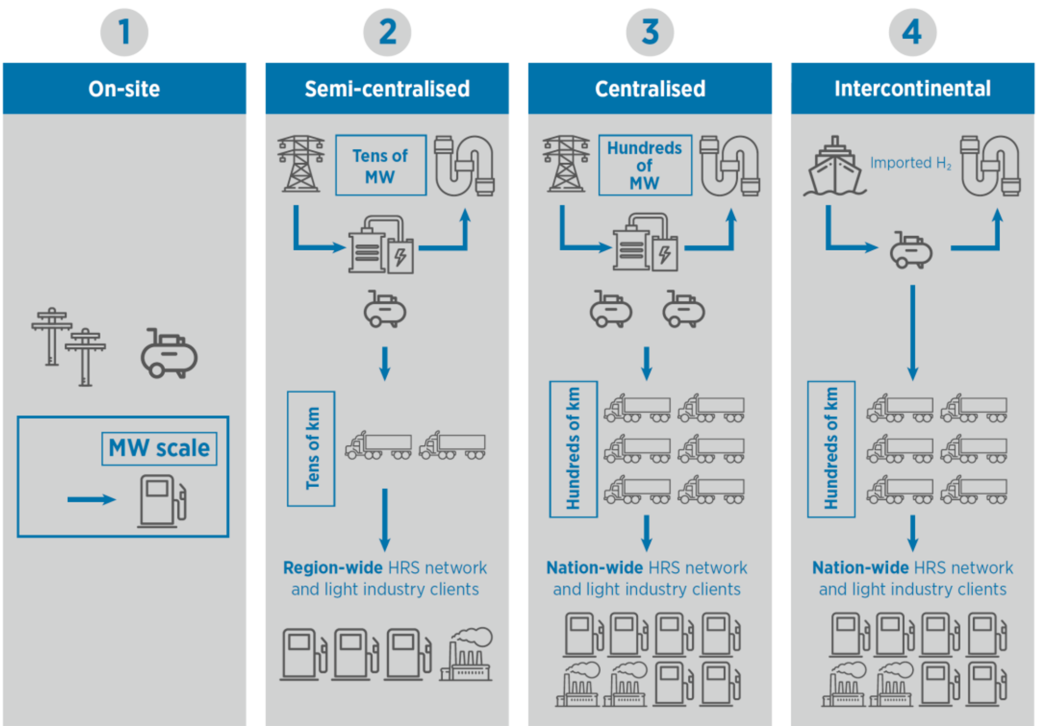

Figure 16. Potential scenario for the future development of the hydrogen supply chain (IRENA, 2018).

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SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES

GEOLOGICAL OCCURRENCE

From https://www.renewablematter.eu/articles/article/natural-hydrogen-a-geological-curiosity-or-the-primary-energy-source-for-a-low-carbon-future

Hydrogen is the most common molecule in the universe. However, in the Earth's atmosphere it exists only in very small quantities at around 500 parts per billion (or 0.5 ppm). Other than trace amounts of gaseous dihydrogen (H_2) at the Earth's surface and above, we find hydrogen essentially combined: with oxygen in water (H_2O) and with carbon in all hydrocarbons (CH_4, C_2H_6 …). However, what is becoming clearer with time is that several phenomena lead to a continuous generation of H_2 in the Earth's crust. A water-rock interaction known as diagenesis releases hydrogen from water during oxidation phenomena that can be observed in different geological contexts. As soon as there is, for example, ferrous iron (Fe^{2+}), in contact with water (sea or rain) it oxidizes to ferric Fe^{3+} and releases H_2. The same reaction can also take place with other metals such as magnesium (Mg^{2+} => Mg^{3+}); it is fast and efficient at high temperatures, around 300°C, but also possible at lower temperatures. Other sources of natural H_2 are known. Another production pathway is radiolysis, by which H_2 contained in water is separated from oxygen by the natural radioactivity of the earth's crust (Sherwood et al., 2014). Estimates of the flow of H_2 through the latter two sources, diagenesis and radiolysis, are important but still not very precise, varying according to the authors from a few percent to 100% of the annual consumption of H_2 in 2019, or approximately 70 million of tons. Other sources such as friction on the fault planes and the activity of certain bacteria also release H_2 but, a priori, in smaller quantities (Worman 2020). What is important to note is that in all these cases it is a flow of H_2 and not an accumulated, fossil resource. At the same time, the preservation of large quantities of primordial H2, the H_2 present at the initiation of the solar system, in the mantle, or even in the earth's core during the formation of the earth is also a working hypothesis explored by some researchers (Larin et al., 2015, Zgonnik, 2020). In this hypothesis, H2 is a fossil resource but almost infinite.

GLOBAL RESOURCES AND RESERVES[1]:

Natural hydrogen (also known as native hydrogen) is generated by geological processes. Emanations of hydrogen have been observed in many places. As a consequence, subsurface accumulations of hydrogen

[1] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of graphite in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template, which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

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drilled “par hazard” and its direct extraction, although still anecdotal today, is beginning to be seriously considered as an abundant source of truly green and inexpensive H_2 (Prinzhofer and Deville, 2015; Moretti, 2019).

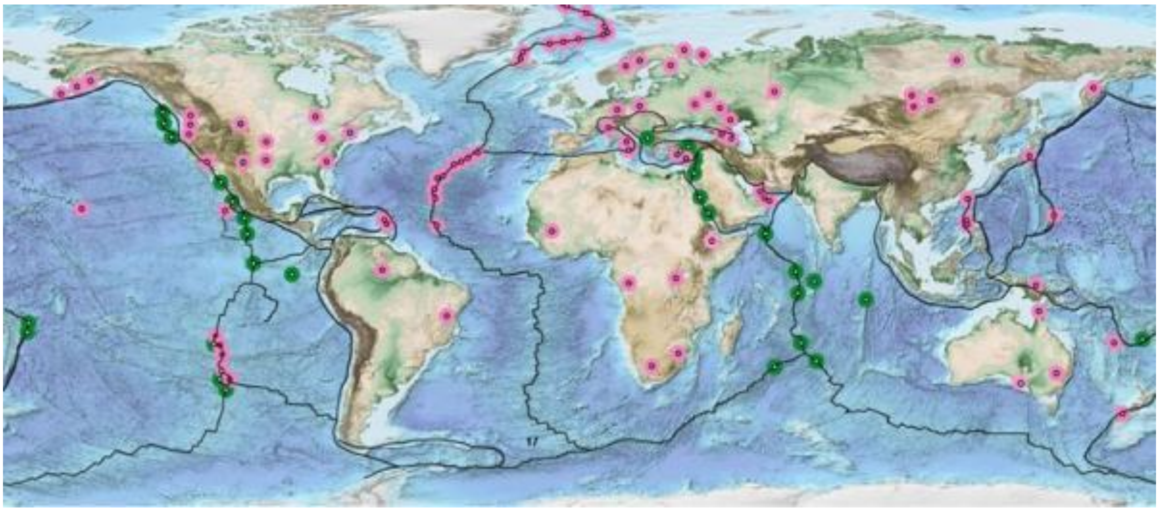

Figure 17 .Map of the already known H2 and CH4 derived from H2 emission

WORLD AND EU MINE PRODUCTION

From https://www.renewablematter.eu/articles/article/natural-hydrogen-a-geological-curiosity-or-the-primary-energy-source-for-a-low-carbon-future

One example of natural H_2 production is particularly compelling. In 1987 a well was drilled in Mali to search for water. The well turned out to be dry, but unexpectedly produced significant volumes of H_2. Aliou Diallo, the director of Petroma (now renamed Hydroma) saw the possibility of local, carbon-free energy in a country that is deprived of it, so the company put the native H2 into production. The well was unplugged in 2011 in order to use it for a pilot to generate electricity for a small village. The hydrogen that comes out of the well is almost pure (more than 96%) so it can be directly burned in a gas turbine. Other surrounding wells have been drilled by Hydroma since 2018 to try to determine the size of the reserves, similar to the early years of oil & gas, and to increase the flows of hydrogen that could be used as feedstock for an ammonia production plant. Part of the results have been published, Prinzhofer et al (2018), and show that all the wells have H2 fluxes. This success has shattered many “a priori”. As of this writing in 2020, the initial well has been producing for 4 years without any pressure decrease from its initial baseline of approximately 4 bars, which implies continuous recharging of the reservoir 110m belowground. The surface measurements of the H2 sensors do not show any leakage, which leads to the conclusion that, contrary to what had been expected given the size of the H2 molecule and its ability to chemically recombine, there are seal rocks that enable an accumulation of H2 and that it can remain in the gaseous phase under our feet. Mr. Diallo and his team have done a lot to draw attention to this basin, especially since H2 can be produced there at much less than a dollar per kilogram, which is significantly cheaper than conventional costs for hydrogen production by electrolysis or steam methane reforming with carbon capture. Unfortunately, because of the complicated above-ground political

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and security situation in Mali, the follow-on work by the scientific community in this location essentially stopped.

Nevertheless, the production data over several years in combination with the search for a low-carbon energy sources has revived interest in the subject and various research and exploration projects have been launched since 2018 (Gauchet 2020). An exploration company dedicated to hydrogen was created in the USA (NH2E) and drilled a first well in Kansas at the end of 2019. In France the company 45-8 Energy holds a mining research permit for helium and H_2, which are often co-located underground.

EXPLORATION AND NEW MINE DEVELOPMENT PROJECTS IN THE EU

Two pilot-scale projects concerning the exploitation and using of hydrogen currently have been planned in EU. The first, "Avants-Monts" program, is going take place in France and aims to the production of hydrogen by the reforming of a stream of hydrocarbons originated by the exploitation of nitrogen-carbon dioxide gaseous deposit. The second, “Guhlen project”, is going take place in Germany aims to the recovery of hydrogen by a mixture of nitrogen-helium-natural gas hosted gas deposit that was discovered in 2012 by the Central European Petroleum (CEP) Company (458energy.com).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Hydrogen is typically vented during industrial processes in the same stream as other waste gas components. The waste hydrogen gas has typically not been recovered for reuse. This is especially true in smaller scale applications, because there is no economical means by which to scrub the gas stream of accumulated impurities, or to compress it in a way that it could be efficiently stored for later use. Hydrogen consumers have traditionally had two solutions to the problem of waste hydrogen: purchase more hydrogen from industrial gas suppliers or generate hydrogen on-site using an electrolyser or a reformer. Recycling rate of 0% can be considered for the calculations.

PROCESSING

Hydrogen is mainly industrially produced through four practices including (Press et al. 2008; Element Energy Ltd, 2018):

- Steam methane (natural gas) reforming
- Gasification (of various feedstocks)
- Partial oxidation of hydrocarbons
- Water electrolysis

methane reforming, gasification and partial oxidation are the dominant technologies in terms produced hydrogen amounts with a 48%, 18% and 30% share, respectively.

The steam methane reforming mechanism comprises the endothermic reaction of a high temperature (700–1100 °C) H_2O steam with methane (CH_4) resulting the formation of a syngas.

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$$CH_4 + H_2O \rightarrow CO + 3\ H_2$$

At a second stage, additional hydrogen is produced via the lower-temperature (360°C), exothermic, water gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Gasification technology permits the transformation and upgrade of a solid fuel (coal, coke etc.) into a mixture of hydrogen and carbon dioxide. This H_2/CO_2 syngas may be separated and purified to produce high purity CO_2 and hydrogen streams.

Partial oxidation of hydrocarbons (oil) is performed in oxidation reactors and a syngas is produced. For example, $C_{24}H_{12}$ in the oil is oxidized according to the reaction:

$$C_{24}H_{12} + 12\ O_2 \rightarrow 24\ CO + 6\ H_2$$

Both methane reforming, gasification and partial oxidation technologies produce high amounts of greenhouse gases.

Water electrolysis consists of an environmentally friendly methodology, however it represents only the 4% of the hydrogen world production. It is performed at the temperature range of 50-80 °C and presents a high efficiency (70-80%). It has a high capital cost and electric energy consumption. There are three main techniques of cell electrolysis: solid oxide electrolyser cells (SOECs), polymer electrolyte membrane cells (PEM) and alkaline electrolysis cells (AECs). PEM consists of the most effective methodology, however it presents a high energy cost due to the use of expensive platinum group metal catalysts. As it can be seen in **Erreur ! Source du renvoi introuvable.**, hydrogen in EU is produced mainly via the fossil fuel – involving technologies.

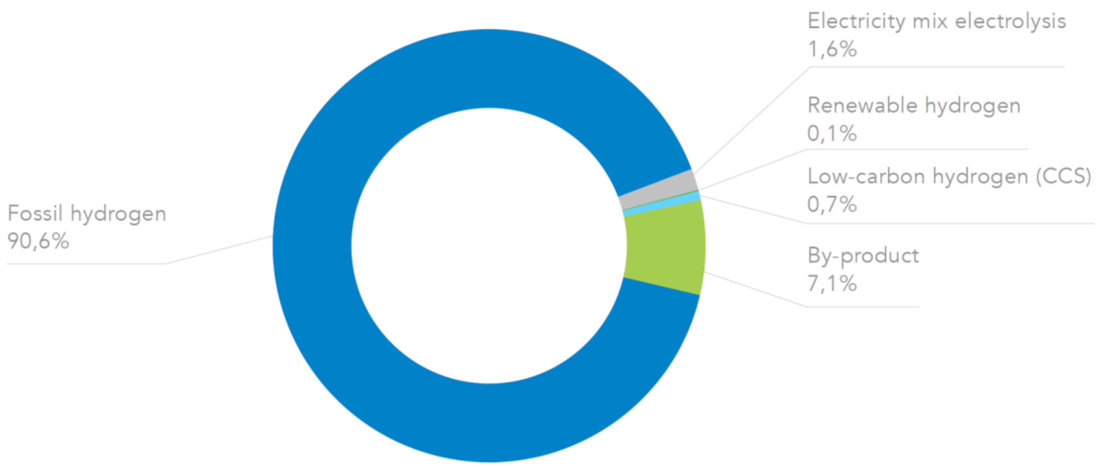

Figure 18. Hydrogen production by technological methodology (Hydrogen Europe Monitor, 2020**).**

According to the European Green Deal presented by the European Commission and based on specific policy initiatives, the greenhouse gas (GHG) emissions should be minimized to zero until 2050. For that matter, green technologies for the production of hydrogen should be exclusively applied. According to a recent study

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(Kakoulaki et al. 2021), carbon-intensive hydrogen production in Europe could be replaced by water electrolysis using electricity from renewable energy resources (RES) such as solar photovoltaic systems, onshore/offshore wind turbines and hydropower. Replacing the annual EU hydrogen production of 9.75 Mt to electrolysis would require 290 TWh of electricity (about 10% of current production). This amount of electricity could be, according to the current infrastructures in EU, potentially covered by green electricity technologies until 2030.

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Hydrogen within the human body is produced as a by-product of microbiota fermentation within the intestinal tract. Within the human body, hydrogen is a naturally produced by-product of fermentation by the microbiota, the development of microorganisms within the intestinal tract; however, production can vary due to factors such as the individual's environment, diet, and overal health. The symbiotic relationship between gut health and immune health continues as studies show the benefits of molecular hydrogen facilitating intestinal fermentation and gut health, even promoting the growth of beneficial short-chain fatty acids.4

ENVIRONMENTAL ISSUES

Hydrogen production is mainly obtained from fossil fuels (i.e. steam reforming of natural gas, coal gasification and partial oxidation of methane)(Holladay et al. 2009; Liu, Song, and Subramani 2009). However, hydrogen can be produced using biomass resources as well (e.g. partial oxidation, plasma reforming, electrolysis of water),through methane pyrolysis (Holladay et al. 2009; Baade, Parekh, and Raman 2001), and via hydrolysis with (surplus) electricity from renewable energy sources (green hydrogen).

Currently Hydrogen is considered a key material to achieve the European Green Deal and energy transition (European Commission 2019; 2020a). Moreover, building on the Commission's New Industrial Strategy for Europe and its recovery plan defined in 2020 the European Union has built a roadmap on how clean hydrogen can be used as a viable source of clean technology(European Commission 2020b; 2020a). As a result, almost all Member have included clean hydrogen in their National Energy and Climate change and in their alternative fuels infrastructure national policy frameworks (European Commission 22 October).

Hydrogen technologies will play an important role in the reduction of greenhouse gases. Nonetheless, in their implementation, lifespan must be addressed taking into account an environmentally friendly materials not only from the manufacturing perspective but also from the end-of-life scope. Currently, hydrogen fuel cell technologies don't have any specific regulation in terms of recycling or end-of life.

STANDARDISATION AND NORMATIVE REQUIREMENTS

The implementation of hydrogen and fuel cell technologies in the current energy and transport systems requires appropriate normative requirements to ensure the environment, health and safety standards.

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Hydrogen (H_2) and Fuel Cell (FC) technologies are developed worldwide, particularly in Europe, Asia, and North America ('ACER H2 Paper_ VFinal_clean.Pdf' n.d.; Léon 2008).

- New Legislative Framework adopted by the European Commission. To improve the internal market of products and strengthen the conditions for placing a wide range of products on the EU market, the new legislative framework was adopted in 2008. Its measures aim to improve market surveillance and measures for products legislations. As a result, stakeholders have to anticipate, synchronize and harmonize the development of standards and regulations (https://ec.europa.eu/growth/single-market/goods/new-legislative-framework_en). The new legislative framework consists of:
    a) Regulation (EC) 765/2008 setting out the requirements for accreditation and the market surveillance of products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008R0765&from=EN
    b) Regulation (EU) 2019/1020 on market surveillance and compliance of products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R1020&from=EN
    c) Regulation (EU) 2019/1020 on market surveillance and compliance of products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R1020&from=EN
- The revision and further development of the Alternative Fuels Infrastructure Directive (AFID) (2014/94/EU), the Global Technical Regulation on Hydrogen and Fuel Cell Vehicles (GTR 13) and the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).
- Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN
- COUNCIL REGULATION (EU) No 559/2014 establishing the Fuel Cells and Hydrogen 2 Joint Undertaking; - The Fuel Cells and Hydrogen Joint Undertaking. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32014R0559&from=EN
- Regulation (EC) No 942/2019 of the European Parliament and of the Council establishing an Agency for the Cooperation of Energy Regulators. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R0942&from=en
    - Review of Directive 2009/73/EC concerning common rules for the internal market in natural gas and Regulation (EC) 715/2009 on conditions for access to the natural gas transmission networks.

Furthermore, the development of hydrogen and fuel cell standards within the framework of the relevant international bodies can be found below:

a) International Organization for Standardization (ISO):
    - Basic Considerations for the Safety of Hydrogen Systems (ISO/TR 15916). ISO/TR 15916:2015 provides guidelines for the use of hydrogen in its gaseous and liquid forms. It identifies the basic safety concerns and risks, and describe the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are treated in separate international Standards
    - Gaseous Hydrogen - Land Vehicle Fuel System Components (ISO 19887)
    - Hydrogen Fuel – Product Specification (ISO 14687). This document has been mainly revised based on the research and development of PEM fuel cells focusing on the following on PEM fuel cell catalyst and fuel cell tolerance to hydrogen fuel impurities; effects/mechanisms of impurities on fuel cell power systems and components; impurity detection and measurement techniques for

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laboratory, production and in-field operations; fuel cell vehicle demonstration and stationary fuel cell demonstration results.

- Fuel Cell Road Vehicle- Energy Consumption Measurement, Part 1: Vehicles fuelled with compressed hydrogen (ISO 23828). This standard specifies the procedures for measuring the energy consumption of fuel cell passenger cars and light duty trucks which use compressed hydrogen and which are not externally chargeable.
- Gas analysis — Analytical methods for hydrogen fuel — Proton exchange membrane (PEM) fuel cell applications for road vehicles (ISO 21087). This document specifies the validation protocol of analytical methods used for ensuring the quality of the gaseous hydrogen (H2) at hydrogen distribution bases and hydrogen fuelling stations for road vehicles using proton exchange membrane (PEM) fuel cells. It also gives recommendations on the calculation of an uncertainty budget for the amount fraction.
- Liquid Hydrogen - Land Vehicle Fuelling System Interface (ISO 13984) This International Standard specifies the characteristics of liquid hydrogen refuelling and dispensing systems on land vehicles of all types in order to reduce the risk of fire and explosion during the refuelling procedure and thus to provide a reasonable level of protection from loss of life and property.
- Liquid Hydrogen - Land Vehicle Fuel Tanks (ISO 13985). This standard specifies the construction requirements for refillable fuel tanks for liquid hydrogen used in land vehicles as well as the testing methods required to ensure that a reasonable level of protection from loss of life and property resulting from fire and explosion is provided.
- Basic considerations for the safety of hydrogen systems (ISO/TR 15916:2015-12) This standard provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety.

b) Canadian Standards Association (CSA):

- Fuel System Components for Hydrogen Gas Powered Vehicles (ANSI/CSA HGV3.1). This standard contains requirements for newly produced compressed hydrogen gas fuel system components, intended for use on hydrogen gas powered vehicles. This standard applies to devices which have a service pressure of either 25 MPa, 35 MPa or 70 MPa.
- Standards for Hydrogen Vehicle Fuel Containers (CSA HGV2). This standard contains requirements for the material, design, manufacture, marking and testing of serially produced, refillable containers intended only for the storage of compressed hydrogen gas for vehicle operation.
- Basic Requirements for Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers (CSA HPRD1). This standard contains requirements for pressure relief devices intended for use on fuel containers.
- Best practices for defueling, decommissioning, and disposal of compressed hydrogen gas vehicle fuel containers (CSA SPE-2.1.3).

c) International Electro technical Commission

- Railway applications – Rolling stock – Fuel cell systems for propulsion -Part 2: Hydrogen storage system (IEC 63341-2).

d) European Committee for Electro technical Standardization (CENELEC)

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- CEN/TC 268/WG 5 - Specific Hydrogen Technologies Applications
- CEN/CLC/JTC 6 - Hydrogen in Energy Systems

SOCIO-ECONOMIC AND ETHICAL ISSUES

Not specific issues

R&D TRENDS

- Production of green hydrogen by means of large-scale electrolysis- Nouryon and ENGIE project (Nouryon, n.d.). https://www.nouryon.com/globalassets/nouryon/4.-company/4.-sustainability/downloads/sustainability-report-2020_en_fullversion.pdf
- Green hydrogen from locally produced solar energy with electrolysers for last-mile transport in urban areas (IRENA 2018). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf
- Renewable hydrogen production by electrolysis instead of steam methane reforming for use in polysilicon manufacturing (Wacker 2021). https://www.wacker.com/cms/en-us/about-wacker/investor-relations/financial-news/detail-154880.html
- FuelCellEurope contribution to the consultation on Roadmap for a low carbon economy by 2050. https://ec.europa.eu/clima/sites/clima/files/docs/0005/registered/88980385100-51_fuelcelleurope_en.pdf
- Green hydrogen and decarburization on an industrial scale (WESTKÜSTE 100 project). https://www.westkueste100.de/en/
- TataSteel project, use of hydrogen in steel making. https://www.tatasteeleurope.com/corporate/news/tata-steel-european-operations-take-major-step-towards-becoming-carbon-neutral
- The Hydrogen Strategy for North Germany is the result of close cooperation of a number of Federal States and of comprehensive and constructive involvement of active players from the areas of business, research and administration. https://www.hamburg.de/contentblob/13874168/e484c76e44486905abd9220bbdd64a8f/data/hydrogen-strategy-for-north-germany.pdf
- Carbon Direct Avoidance by replacing carbon in iron ore reduction processes with hydrogen in Germany. Additionally, process heat for steelmaking by electrical energy instead of coal. https://salcos.salzgitter-ag.com/
- Hydrogen Breakthrough Ironmaking Technology to produce fossil-free steel by 2035 in Sweden. https://www.hybritdevelopment.se/
- CO2 from the steel industry in the port of Ghent is converted into methanol via methanol synthesis with green hydrogen. https://stad.gent/nl/ondernemen/economische-speerpunten/cleantech-cluster-regio-gent/projecten-partnerschap/carbon-capture-utilization-hub

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- Upscaling of green H2 for mobility and industry by investment in green H2 value chain from production in electrolysis, trailer loading and FCV refuelling station in Austria. https://projekte.ffg.at/projekt/3093345
- New combination of existing technologies (H2 from natural gas, CCS, hydrogen burning) and use of hydrogen to replace natural gas/coal burning & decarbonise refinery fuel gases in the Netherlands. https://www.deltalinqs.nl/h-vision-en

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