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Briefing 25

Methods of producing hydrogen

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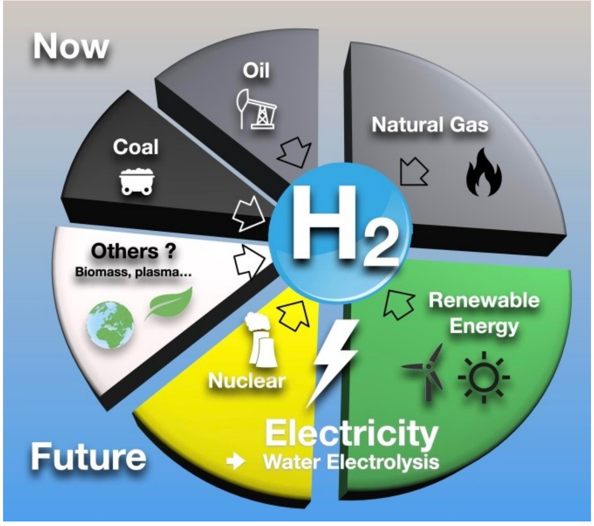


Source: OPECST

Summary

- *Today, hydrogen production relies on fossil fuels (natural gas, oil and coal) and generates high levels of greenhouse gas (GHG) emissions.*
- *Although it is far from being a miracle solution, hydrogen can become a useful energy carrier if it is produced in an environmentally friendly way, either by capturing carbon when fossil fuels are used or by using nuclear or renewable electricity when it is produced through water electrolysis.*
- *The second technique, on which France is justifiably but exclusively taking a chance, is more expensive and requires water and electricity. It does not provide a guarantee of carbon neutrality. Other low-carbon hydrogen production methods, although poorly developed and often more expensive, are still worth considering, both in terms of research and industrial development.*

Gérard Longuet, Senator, First Vice President

From the miraculous energy source prophesied by Jules Verne...

First discovered by Paracelsus around 1520[(1)] and named hydrogen by Lavoisier in 1783 since this gas can produce water (the meaning of the two Greek words "Hudôr" and "Gennen", which are combined in the word "Hydrogen"), when combined with oxygen, this "flammable air", according to Cavendish's formula, has been the subject of a considerable amount of research and has various uses. In *The Mysterious Island* (1874), one of Jules Verne's characters says: "*I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable"*. To this day, neither water nor the most abundant element in the universe, hydrogen, have become inexhaustible energy sources: at best, this gas, **in its molecular form of dihydrogen** H_2, can be considered a useful energy carrier[(2)] whose potential has yet to be developed in the long term. Hydrogen itself is a **paradox**. It is the most common element in the universe, but it is **rarely found in its molecular state here on earth.**[(3)] It is extremely light (eleven times lighter than air) and can easily escape from our atmosphere.[(4)] It can be found **combined with other elements** (60% of molecules contain hydrogen), such as oxygen (water=H_2O) or carbon (organic matter or methane=CH_4 for instance). Before it can be used or stored, it needs to be **produced by expending energy** to separate it from the elements with which it is combined. There are many more or less costly and GHG-emitting techniques: hydrocarbon conversion, water electrolysis, thermo-chemical decomposition of water or biomass, etc.

... to actually producing hydrogen by transforming fossil fuels

The most commonly used production methods - representing **99%** - are those involving **fossil fuels**, which are less expensive but emit high levels of GHGs. According to the International Energy Agency[(5)], of the **70 million tons of hydrogen** produced around the world each year, (not including as co-product), one million of which is produced in France, 48% is obtained from natural gas, 28% from oil and 23% from coal. While there are dozens of non-hydrocarbon based hydrogen production techniques, their use is limited by their cost, complexity and lack of development. The most commonly used technique is **steam methane reforming (SMR)**. This involves removing the sulphur from the natural gas, then treating it with steam at about 900°C and at a pressure of 20 to 30 bars.[(6)] A nickel catalyst is then used to transform the gas into a syngas (a mixture of H_2, CO, CO_2, CH_4 & H_2O). Then, the hydrogen is isolated using *Pressure Swing Adsorption* (PSA) technology, which is a kind of molecular sieve. Another production technique is the **partial oxidation of hydrocarbons** (or Pox for *Partial Oxidation*), which mainly involves oil and its by-products. In this intermediate process between pyrolysis and combustion, the syngas - instead of using a catalyst and steam as with the

SMR technique - is produced via an exothermic reaction with oxygen under increased temperature and pressure (900 to 1,500°C and 20 to 60 bars). These two production methods produce what is known as "grey" hydrogen. **Coal carbonisation** has been used by several countries in the past,[7] but was not really used until China, which produces half of the world's coal and has become the world's largest hydrogen producer with this technique, started to use it on a massive scale about 15 years ago. This process produces what is known as "black hydrogen". There are also processes for converting hydrocarbons into hydrogen, known as hybrids between SMR and partial oxidation,[8] which are of interest for producing large volumes of hydrogen (from 500,000 m3/h), such as the ATR (*autothermal reforming*) technique. Today's most common methods of producing hydrogen by converting fossil fuels also produce **high levels of greenhouse gases** (around 800 million tonnes of CO_2 per year, compared with the total of 37 billion tonnes of CO_2 produced by the combustion of fossil fuels).

CO2 capture/CCS

To limit the environmental impact of GHGs emitted by producing hydrogen from fossil fuels, CCS (*Carbon Capture and Storage*) is one suitable option, provided that it is permanently and safely stored in geological formations. **Its cost - around €200/t of CO_2 in the short term, which can be reduced to €50/t of CO_2 in the long term - would represent an additional cost of €500 to €2000/t of hydrogen produced** (i.e. +30 to +125%). Several projects are currently underway (some dating back to 1996), notably in the North Sea, with the help of active and highly qualified research companies, including the French companies Ifpen, Air Liquide, Total, Engie and Storengy. 40 million tonnes of CO_2 are already being captured each year.

The challenge of low-carbon hydrogen production through water electrolysis

The preferred way to produce low-carbon hydrogen is to **use electrical energy to extract the hydrogen from water through electrolysis**. This process of extracting hydrogen from the cathode and oxygen from the anode is simple and well established (implemented as early as 1800) but is difficult to scale up due to the high costs involved. As well as requiring significant investment, 80% of operating costs are determined by the price of electricity, with electrolysers consuming on average 55 kWh of electricity and 9 litres of water per kg of hydrogen produced. There is also the issue of **how the electricity is produced**. If it is produced using coal or other fossil fuels, water electrolysis can have an even larger carbon footprint than directly separating hydrogen from natural gas or coal. For the hydrogen produced by electrolysis to be low-carbon, it needs to be produced using "green" electricity - from renewable energy sources (RE) - or "yellow" electricity - from nuclear energy. However, this production method is not economically attractive. It costs **four times as much as SMR** and depends largely on the price of electricity, the price of electrolysers and the load factor of these electrolysers. As investments are high, electrolysers need to be made more cost-effective by extending their useful life (minimum threshold of 5,000 h/year and optimum threshold of up to 8,000 h/year), which is simply not possible due to the **intermittent availability of renewable energy sources** (2,000 to 4,000 h/year of use). In this respect, **only nuclear energy and hydroelectricity have the double advantage of being both sustainable and decarbonised.**

There are **three types of electrolysers**, each of which is developed by French companies at the cutting edge of innovation: 1) a long established and proven technology based on alkaline electrolysers[9] (of which Mc Phy is a recognised manufacturer), 2) a more recent technology which has yet to be developed industrially, based on proton exchange membranes or PEM[10] (of which Elogen, formerly Areva H2Gen, is a specialist), and 3) a very promising but not yet technologically developed high-temperature technology, the solid oxide electrolyser or SOEC[11] (in which the CEA, Genvia and Sylfen are leading players, with the objective of 1 MW in 2024 and 300 MW in 2030). In addition to public support, the development of electrolysers will be encouraged by improving their efficiency, optimising their production and reducing their costs through economies of scale, which will be made possible by industrialisation and greater production volumes.

Other production techniques

In addition to producing fatal hydrogen, which is usually recovered,[12] there are other techniques that are costly, complex and/or not very well developed: producing hydrogen by thermo chemically decomposing water,[13] by oxidising iron, through photosynthesis (using micro-organisms such as algae and bacteria) or through bio-mimetic processes - photocatalysis and photoelectrocatalysis. Particular attention should be paid to **two readily available** and more affordable solutions. The first is **methane pyrolysis** (where the carbon resulting from the production process remains in the solid form of "black carbon" and not CO_2) which is a very efficient process, particularly thanks to plasma technologies that were first introduced back in 1920. Some of these technologies have since been perfected by the Ecole des Mines de Paris and are currently deployed on an industrial scale by the American company Monolith Materials. The second solution is **producing hydrogen from biomass**, which is very advantageous[14], as it is illustrated in the table below, even though it is in direct competition with methane production. Haffner Energy is currently starting up the first biomass thermolysis hydrogen production units in Strasbourg (at a cost of less than €5/kg).

A comparison of the main hydrogen production methods

Technology	Steam reforming	Partial oxidation	Carbonisation	Electrolysis	Pyrolysis (incl. plasma)	Thermolysis	Thermo-chemical decomposition
Raw materials used	Methane, oil by-products...	Oil by-products...	Coal	Water+electricity	Methane	Biomass	Water+electricity (or other forms of energy)
Share and volume / world production	48 % 33.6 million t.	28 % 19.6 million t.	23 % 16 million t.	<1 % <700,000 t.	Almost zero	Almost zero	Almost zero
Colour*	Grey (blue - if CCS)	Grey (blue - if CCS)	Black (blue - if CCS)	Green - if RE Yellow - if nuclear	Turquoise	Green (to be confirmed)	No colour
Estimated cost (Europe)	€1,600/t (+ €500 to €2,000 if CCS)	€1,660/t (+ €500 to €2,000 if CCS)	€1,000/t (+ €1,000 to €3,000 if CCS)	€4,000 to €6,000/t (the least expensive: alkaline - the most expensive: SOEC - between the two: PEM) €2,000 to €3,000/t in the long-term	€1,660/t €350 to €850/t in the long-term	€2,000 to €6,000/t depending on the size of the units	Very uncertain - in the R&D phase (>€300/t)
Maturity	+++	+++	+++	+	-	-	- - -
Efficiency	72 to 82 %	53 to 67 %	50 to 70 %	70 % (up to 85 % for SOEC)	50 %**	70 %	Low
Emissions - tonnes of CO_2 per tonne of hydrogen produced - life cycle analysis (LCOE calculation)	9 to 13 (<5 if CCS)	13 to 18 (<5 if CCS)	20 (open pit mines) 24 (underground mines) (less if CCS)	Depends on the origin of the electricity used, low if RE or nuclear (21 according to US mix and 3 according to French mix)	Depends on the origin of the electricity used (4 depending on the American mix and zero or negative if RE)	Low, zero or negative (-15 if the Biochar produced is returned to the ground.)	Depends on the origin of the electricity used, low if RE or nuclear
Examples of French companies	Air Liquide & Ifpen	Air Liquide, Total & Ifpen	Ifpen (via Axens)	McPhy, Elogen (previously ArevaH_2Gen), CEA, Genvia, Sylfen, EDF, Air Liquide & Engie	-	Haffner Energy et sa technologie Hynoca & Trifyl	-
Examples of foreign companies	Air Products, Linde, Praxair, Airgas, Messer, Amec Foster Wheeler & Technip FMC	Air Products, Shell, Mitsubishi, Conoco Philips, Exxon, Chevron & BP	Shenhua/ Guodian, Datong, Sinopec, Baofeng, Air Products & Conoco Philips	Siemens, Thyssenkrupp, Cockerill, Asahi Kasei, Nel, ITM, Sunfire, Schlumberger & Cummins (Hydrogenics)	Monolith Materials	Air Products	-

***** Colour code used by the European Union until 2020 and still used in Germany and in a number of research operations

****** The efficiency of hydrogen production by methane pyrolysis is 50% but with eight times less energy required than electrolysis for the same amount of hydrogen produced.

NB: CCS = Carbon Capture and Storage; RE = renewable energy sources; SOEC = Solid Oxide Electrolysis; PEM = Proton Exchange Membrane electrolysis; ACV = life cycle analysis; LCOE = *Levelized Cost of Energy*

Source: Opecst based on information from IEA, Afhypac, Ademe, Ifpen, Haffner, Monolith Materials and the article "Levelized Cost of CO2 Mitigation from Hydrogen Production" by B.Parkinson et al., published in the "Energy & Environmental Science" journal in January 2019.

In the short term, **grey hydrogen is the cheapest to produce** - around €1.6/kg - **but low-carbon hydrogen** is expected to be developed further and **cost less in the future,**[15] whether green (from €4-6/kg to €2-3/kg), yellow (from less than €3/kg to less than €2/kg) or even blue (lower CCS costs). Grey hydrogen, on the other hand, is expected to increase in cost due to higher CO_2 prices and the expected increase in the price of natural gas.[16]

■ The challenges involved in hydrogen production

Given current climate concerns, **it has become increasingly important to use low-carbon methods of producing hydrogen**. The aim is both to satisfy the **existing uses** of hydrogen,[17] i.e. industrial applications (80% for oil refining and ammonia production, which is used in fertilizers, and the rest to produce methanol, polymers, hydrogen peroxide, etc.), but also to **anticipate new ways of using hydrogen as an energy carrier**, in particular to **transport large amounts of energy,**[(18)] or even to store surpluses resulting from the intermittent supply of renewable energy.[(19)] However, this may lead to underused electrolysers and the risk of additional costs, especially with regard to the proposed target of €2 to €3/kg. By using a *power to gas to power* loop, we can effectively transform hydrogen into methane, via methanation, or into electricity, via fuel cells. In addition, the maximum direct injection into the natural gas network, currently limited to 6%, could be increased.

Besides being the most flammable and lightest gas, capable of escaping from almost anywhere, **hydrogen is by no means a miracle solution;**[(20)] the overall process is **not very efficient**. This is largely due to the fact that the multiple conversions needed to produce it result in a lower energy potential. For instance, according to Ademe, the efficiency of the hydrogen chain for a hydrogen electric vehicle, from production to final use, is approximately 22%.[(21)] Furthermore, **distributing hydrogen** remains an **extremely delicate and expensive** process. The incredibly low density of hydrogen (0.09 kg/m3) means that, even when stored at a pressure of 350 bar, it takes up 13 times more space than petrol. As the Academy of Technology explains in its report,[(22)] a realistic understanding of the entire hydrogen value chain is needed before we can establish hydrogen as a viable solution for achieving carbon neutrality. In this respect, decentralised hydrogen production may be of great interest.[(23)]

The National Strategy for Decarbonised Hydrogen

Following the hydrogen plan of 1 June 2018, on 8 September 2020, France announced a strategy geared towards supporting renewable hydrogen and low-carbon hydrogen (i.e. from renewable energy sources or nuclear electricity, as opposed to carbon-based hydrogen, this distinction having been made in the Government Ordinance of 17 February 2021 concerning hydrogen). With a budget of €7 billion between now and 2030, led by a coordinator since February 2021 and guided by a national council and an observatory, this strategy places a high priority on industry rather than research (€80 million, i.e. just over 1% of the funds) and opts exclusively for hydrogen production by water electrolysis.

The European Commission supports an even narrower target for electrolysis production, fuelled by renewable energy alone, and nuclear power is not mentioned in the European hydrogen strategy presented on 8 July 2020.

The European target of installing 6 gigawatts (GW) of electrolysers to produce one million tonnes of renewable hydrogen by 2024, and then 40 GW for ten million tonnes by 2030, must be set against the number of wind turbines and solar panels that these figures could represent[(24)]: at least 15,000 and 150,000 wind turbines respectively, on the one hand, and in terms of the area needed for solar panels, about 80,000 hectares and nearly one million hectares, on the other hand. To meet the current needs of industries worldwide (70 million tonnes of renewable hydrogen, or 420 GW), more than **one million new wind turbines would have to be installed, or 5 to 6 million hectares of new solar panels.** Alternatively, producing low-carbon hydrogen using nuclear power would require 400 new 1 GW nuclear reactors. This option seems highly unlikely, especially at a time when most countries, including our own, are trying to reduce the amount of nuclear power in their energy mix. Some countries, including Germany, aim to import renewable hydrogen from countries with greater renewable energy capabilities.

■The Office's recommendations

In 2013, in its report entitled "Hydrogen: an energy carrier for energy transition?"[(25)] the Office recommended coordinating the efforts of all those involved in developing this industry - from production and storage, to the use of hydrogen energy - and bringing them together. These recommendations remain valid. With specific regard to promoting low-carbon hydrogen, the Office recommends:

- using carbon capture and storage (CCS) when producing hydrogen from fossil fuels, and ensuring that when producing hydrogen by water electrolysis, the electricity used is of nuclear or renewable origin, which will require rigorous traceability mechanisms;

- developing hydrogen production technologies using water electrolysis (alkaline, PEM or SOEC), which are suitable, but not exclusive, as other hydrogen production methods should not be overlooked, both in terms of research and in terms of industrial applications. For example, methane pyrolysis and producing hydrogen from biomass are both highly interesting techniques. Efforts will need to be made to accelerate their development;

- considering the use of the price per tonne of CO_2 to internalise the cost of GHG emissions and make low-carbon production more competitive. Setting this price at €250/t would mean that green or yellow hydrogen could compete with grey hydrogen produced by converting hydrocarbons. Between €100 and €200/t would, *at the very least*, encourage the use of CCS, thus switching from grey to blue hydrogen;

- supporting research on hydrogen production, including materials, and improving knowledge of natural hydrogen.

Significantly increasing our low-carbon electricity generation capacity could help revive the nuclear sector, but the future of hydrogen will depend on a **coherent, realistic and responsible energy policy.**

This ambition needs to be more than just a slogan; **otherwise, hydrogen, which has long been a technology of the future, will remain that way.**

The Office's websites:

http://www.assemblee-nationale.fr/commissions/opecst-index.asp
http://www.senat.fr/opecst

Références

[1] Paracelsus was the first to demonstrate the phenomenon of gas emission when vitriol (concentrated sulphuric acid) reacts with iron. Cavendish only discovered hydrogen as a separate element in 1766.

[2] An energy source is available and usable while an energy carrier, such as electricity or hydrogen, is used to transport energy, with losses (i.e. a carrier will release less energy than it took to produce it).

[3] Natural hydrogen is mainly produced at the bottom of the sea, most often at great depths, which makes it difficult to collect. Hydrogen emanations could also be identified on earth, depending on geological conditions that need to be further investigated. There are several types of geological situations in which hydrogen can be separated from water: on the one hand, radiolysis occurs due to the natural radioactivity of certain rocks and, on the other hand, iron oxidation occurs in rocks that have a high metal content. The natural oxidation of the ocean floor, known as serpentinization, has also been observed in peridotite masses where the tectonic context leaves the rocks exposed to alteration by meteoric waters. Precambrian cratons, the oldest areas of the emerged continents, can also be subject to such a phenomenon. An accumulation of natural hydrogen discovered in Mali in 1987 while drilling in a cratonic zone is currently being used to produce electricity. However, the energy produced remains rather modest, especially considering that a 35 kilovoltampere electric turbine generates 7 kW of power. More research is needed to identify our planet's natural hydrogen reserves and to understand how they were formed.

[4] Because of its light weight, hydrogen has an endosmotic property that enables it to pass through small openings and membranes with greater ease than any other gas.

[5] See the International Energy Agency (IEA) report on the future of hydrogen, published in 2019.

[6] This temperature of 900°C and pressure of 20 to 30 bar is the ideal level to minimise costs. After the first nickel-catalysed reaction, additional hydrogen can produced by steam reforming in a second reaction at a lower temperature - at 400°C with an iron-chromium catalyst and at 200°C with a copper-iron catalyst.

[7] Coal liquefaction and carbonisation - used to produce synthetic gasoline and syngas - were used extensively by Nazi Germany in the 1930s and 1940s, following the development of the Fischer-Tropsch process in 1920. At the time, the aim was to overcome the dependence on oil. Since then, only South Africa has continued to mass produce such synthetic products, and this is mainly due to blockades. China is one of the world's leading coal producers, especially since the 2000s and 2010s, and uses it for a wide range of applications, including hydrogen production.

[8] The choice of technique most often depends on its relative cost, the volume of hydrocarbons converted to H_2, the type of hydrocarbon used and the versatility of the process with respect to the type of hydrocarbon being processed.

[9] Alkaline water electrolysis, which has a long history in the chemical industry, uses an aqueous solution of potassium hydroxide (potash), whose concentration varies according to temperature (typically 25% at 80°C). It consumes 55 kWh per kg of H_2 produced (70% efficiency) but there is still room for improvement.

[10] Proton Exchange Membrane (PEM) electrolysis, which is 25% more expensive, is 75% efficient and has been used to generate oxygen in the space sector and in nuclear submarines for several decades. It involves the use of an acidic solid electrolyte with a proton-conducting polymer membrane that requires noble metals (platinum, iridium, etc.) and a temperature of 65 to 70°C. It is suitable for renewable energy sources as electrical power variations do not affect its operation, unlike alkaline electrolysis, which is expensive to maintain (corrosion linked to the liquid electrolyte, etc.).

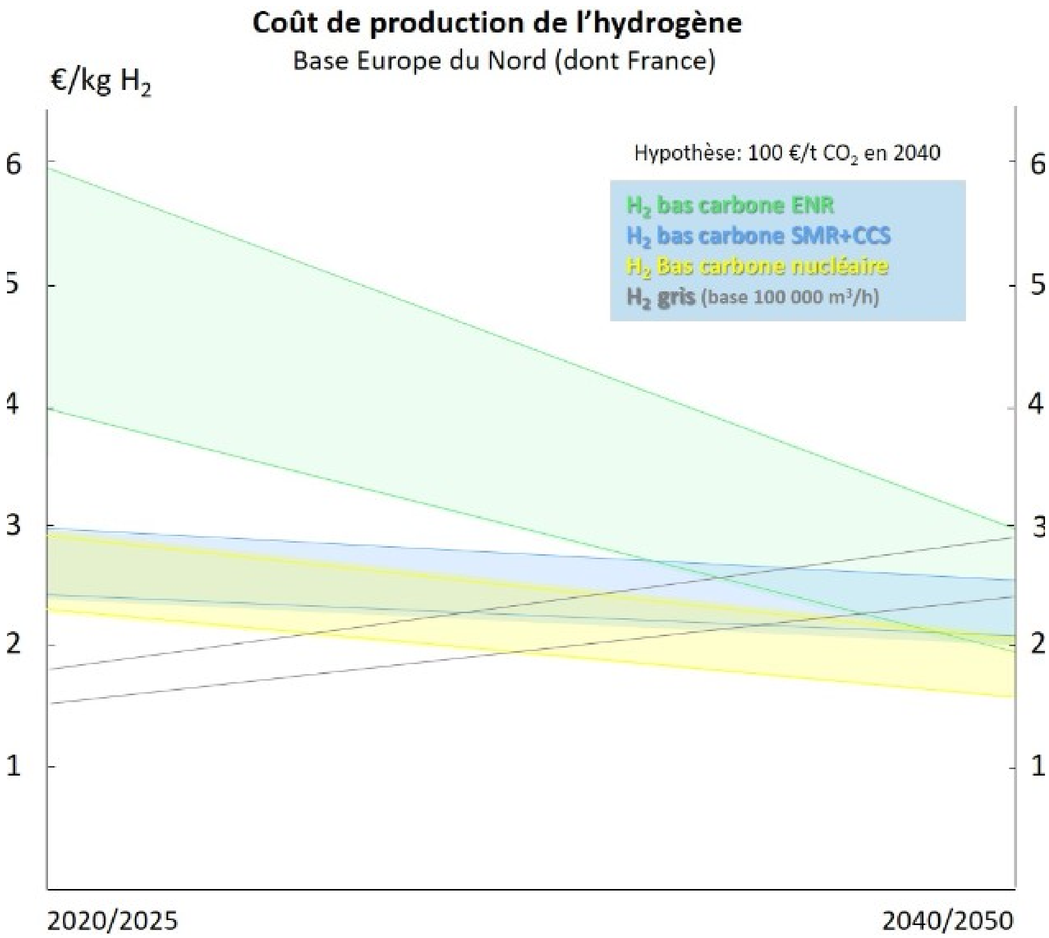
[11] Developed from advances in fuel cells, SOEC (solid oxide electrolysis cell) electrolysis is 25% more expensive than the PEM method and operates at extremely high temperatures (400 to 1,000°C) with an efficiency of 85%, provided that there is sufficient waste heat (at least 150°C) available to vaporise the water and without using noble metals. These electrolysers must therefore be combined with a heat source, such as a concentrated solar energy system or high-temperature nuclear reactors ("4th generation"), which involves both the nuclear and hydrogen industries. They also have the advantage of being reversible (the electrolyser is also a fuel cell). Its PCEC (protonic ceramic electrolysis cell) variant does not work by transferring negative ions, but by transferring protons, still within a ceramic but at a lower temperature of 350 to 600°C.

[12] Fatal hydrogen, i.e. hydrogen that is co-produced during industrial processes, represents half of the hydrogen produced in France (total of 900,000 t). It comes from refineries, coking plants and other industrial processes (notably those that involve the use of chlorine). Fatal hydrogen should be systematically recovered.

[13] Water molecules can only be broken down at temperatures above 3,500°C (for thermal break down at atmospheric pressure), which is extremely costly. To break down water at a lower temperature of 900 to 1,000°C, this drop in temperature must be compensated for by adding electrical or chemical energy (e.g. via thermo-chemical decomposition cycles involving iodine-sulphur, zinc, bromide, sulphates, and so on), which results in a low efficiency of around 20%. The two decarbonised heat sources that are capable of providing such an energy input are high-temperature nuclear power (with 4th generation reactors) and concentrated solar energy. The CEA stopped research in the field of thermo-chemical decomposition at the beginning of the 2010s, while Japan continues to develop this technology.

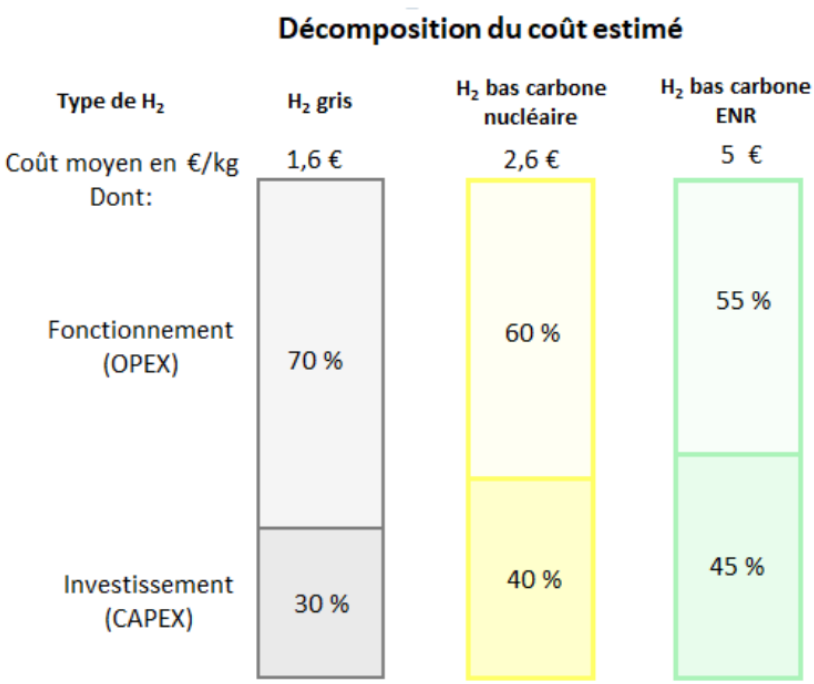
[14] Biomass, which is made up of organic plant and animal matter formed from carbon and hydrogen molecules, can already be used to produce electricity and heat by combustion (30% electricity, 70% heat) by transforming agricultural, forestry, agro-industrial and household waste; methane by anaerobic fermentation of fermentable waste (steam reforming this methane can produce hydrogen); methanol by high-temperature carbonisation of waste that is not particularly fermentable (the syngas generated by the carbonisation process contains hydrogen, so it is also possible to recover this hydrogen instead of using it to make methanol-CH_3OH)

[15] This probable medium and long term development for these four production methods is highlighted in the graph below (the rate of development depends largely on the price per tonne of emitted CO_2):



Source: Claude Heller, Senior Advisor

[16] In order to gain a better understanding of these costs and their fluctuations, we need to specify the differences in structure between operating and investment expenditure, depending on the production method used. Grey hydrogen requires less investment (30% of the total cost) than yellow (40%) and green (45%) hydrogen, and more than 90% of its operating costs are determined by fossil fuels such as methane. The share of operating expenses related to producing yellow hydrogen (60%) and green hydrogen (55%) is largely attributable to the cost of electricity (80%). In the long term, these last two production methods should see the share of investment in their cost fall to around 20% and 30% respectively, thus bringing them into line with the cost structure of grey hydrogen. The breakdown of this estimated cost of hydrogen, depending on the production method used, is shown in the graph below. The differences between the share of operating expenditures (or OPEX) and capital expenditures (or CAPEX) are as follows: the cost of raw materials is clearly the main factor (more than 90% for fossil fuels when it comes to grey hydrogen and 80% for electricity when it comes to yellow and green hydrogen). The remainder is divided between maintenance, labour and other running and operating costs.



Source: Claude Heller, Senior Advisor

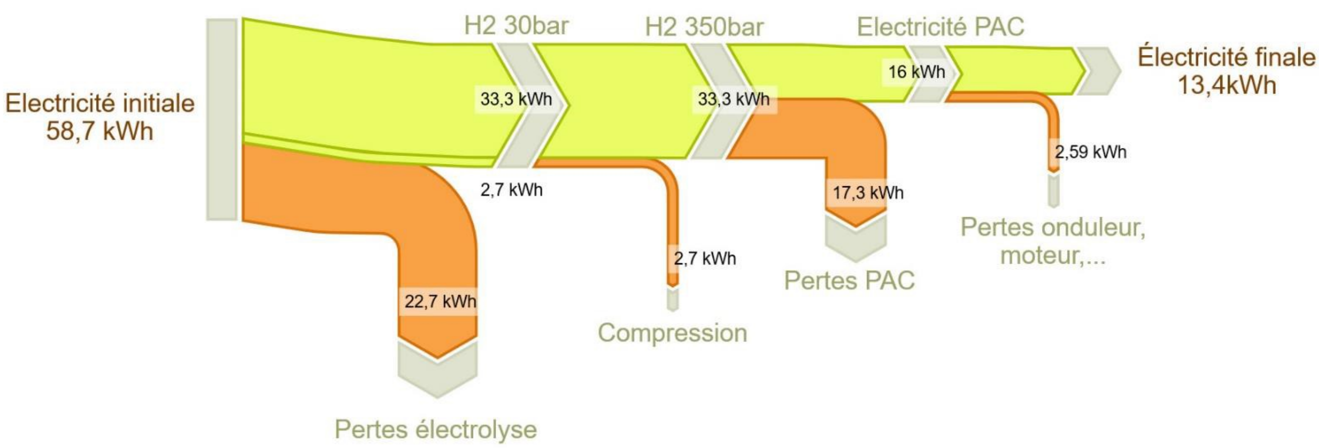
[17] *The International Energy Agency estimates that by 2030, ammonia and methanol production will require 323 billion m^3/year of natural gas (with CCS) or 3,020 terawatt hours per year of electricity to produce low carbon hydrogen.*

[18] *Applications could include public transport (trains and buses) and commercial vehicles (trucks, etc.), as it will be difficult to convert these into to electric vehicles due to the heavy weight of the batteries, a major limitation, which makes hydrogen a more appropriate option. The price of hydrogen at the pump (around €10 to €12/kg at Air Liquide for a maximum range of 100 km/kg of H_2) is not yet competitive (unless the price of fuel - diesel or petrol - increases to more than €2 per litre for conventional petrol/diesel cars that consume 5 L/100 km). In 2019, the Office published a report on phasing out the use of internal combustion vehicles by 2040, drafted by Stéphane Piednoir, Senator, and Huguette Tiegna, Member of Parliament (Link: Office Report 380, 2018-2019).*

[19] *See the Science and Technology Briefing No. 11 on electricity storage, drafted by Senator Angèle Préville.*

[20] *However, various techniques and procedures have been put in place to improve its safety: storage and transport in perfectly sealed composite materials, increased monitoring, etc.*

[21] **From the energy needed to produce one kg of hydrogen to the final amount of electrical energy available**



Source: Ademe

NB: It should be noted that this efficiency of 22% may deteriorate even further, depending on which transport solution is chosen.

[22] See [The Academy of Technology's "The role of hydrogen in a decarbonised economy" report from June 2020].

[23] Approaches that cover the entire chain from production to utilisation are therefore of great value and could, as an example, be beneficially applied to the entire building sector.

[24] These data are based on the ratio empirically observed between our 8,000 wind turbines in operation in France and their annual production of 32 TWh/year (with installed capacity of 15 GW). In regards to photovoltaic panels, the order of magnitude of 80,000 hectares, subject to significant variation margins, retains an approximate intermediate value between 104,000 hectares and 57,000 hectares (these two values being derived, on the one hand, from the meta-analysis by John van Zalka and Paul Behrens which uses an effective power of 6 W/m^2 or 6 MW/km^2, or 525 MWh/year/ha, and, on the other hand, a calculation of Jean-Marc Jancovici which results in 11 W/m^2 or 11 MW/km^2, or 1000 MWh/year/ha).

[25] The Office report 253 (2013-2014) by Laurent Kalinowski and Jean-Marc Pastor is available on the Senate website https://www.senat.fr/rap/r13-253/r13-253.html and on the Assemblée Nationale website https://www.assemblee-nationale.fr/14/rap-off/i1672.asp. The President of the Assemblée Nationale's study group on hydrogen, MP Michel Delpon, published the book "Hydrogène renouvelable. L'énergie verte du monde d'après" (Renewable hydrogen. The green energy of the future) in March 2021.

Note: Gérard Longuet an Independent Director at Cockerill.

Persons consulted

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Institutions

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- Mr. Lionel Prevors, Hydrogen Project Manager

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The French Academy of Technology
- Mr Bernard Tardieu, member of the French Academy of Technology and Chairman of its "Energy and Climate Change" Commission
- Mr. Marc Florette, member of the French Academy of Technology, coordinator of the Academy's report on hydrogen, and former Digital Director at ENGIE
- Mrs. Isabelle Moretti, member of the French Academy of Technology, Researcher at the University of Pau and the Pays de l'Adour, Administrator at the French National Institute for the Industrial Environment and Risks (INERIS), former Scientific Director at ENGIE and former researcher at the IFPEN

International Energy Agency (IEA)
- Mr. Paul Lucchese, hydrogen expert and President of the International Hydrogen Technical Cooperation Program (TCP), in charge of energy systems forecasting at the CEA's Energy Directorate, and former Assistant Director of the Capénergies centre of competitive excellence

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The French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives - CEA)
- Mrs. Hélène Burlet, Assistant Director of Programmes and Projects
- Mr. Laurent Antoni, Programme Manager at CEA-Liten, hydrogen specialist and President of *Hydrogen Europe Research*
- Mr. Vincent Artero, Research Director and specialist in fundamental research on hydrogen production
- Mr. Daniel Iracane, International Strategy Advisor and former Deputy Managing Director and Cheif Nuclear Officer at the Nuclear Energy Agency (NEA)
- Mr. Jean-Pierre Vigouroux, Public Affairs Officer
- Mr. Stéphane Laveissière, Public Affairs Coordinator

The French Institute of Petroleum (IFP Energies nouvelles - IFPEN)
- Mr. François Kalaydjian, Director of Economics and Monitoring and Hydrogen Coordinator
- Mrs. Hélène Olivier-Bourbigou, Associate Scientific Director
- Mr. Jean-Pierre Burzynski, Director of the Results and Processes Centre and Director of Axens

University researchers and researchers from the French National Centre for Scientific Research *(Centre national de la recherche scientifique - CNRS)*

- Mr. Laurent Fulcheri, Professor and Research Director at the École des Mines - MINES ParisTech and Advisor to the company *Monolith Materials*
- Mr. Olivier Joubert, Professor at the Université de Nantes and Director of the Hydrogen Research Federation
- Mr Abdelilah Slaoui, Research Director, Head of the CNRS Energy Unit, and Associate Scientific Director of the Institute for Engineering and Systems Sciences (Institut des sciences de l'ingénierie et des systèmes - INSIS)
- Mrs. Nathalie Kroichvili, Professor at the Université de technologie de Belfort-Montbéliard and head the RECITS (Research and Study on Industrial, Technological and Societal Change) policy at the FEMTO ST (Franche-Comté Electronics Mechanics Thermal Science and Optics – Sciences and Technologies) Institute
- Mrs. Marie-Thérèse Giudici-Orticoni, Research Director and Director of the Institute for Microbiology, Bioenergy and Biotechnology (IM2B) at the Université Aix-Marseille and of the hydrogen biomass online platform
- Mrs. Valérie Keller-Spitzer, Research Director, Director of the Institute of Chemistry and Processes for Energy, Environment and Health (ICPEES) at the University of Strasbourg, the Laboratory of materials, surfaces and processes for catalysis (LMSPC), the SolarFuels research group and the Photocatalysis reserach group
- Mr. Dominique Pécaud, Lecturer, Director of the Institute of Humans and Technology (Institut de l'Homme et de la Technologie) at the École Polytechnique de l'Université de Nantes (Polytech Nantes) and associate researcher at the CRC MINES ParisTech

Companies and associations

France Hydrogène (French Association for hydrogen and fuel cells or AFHYPAC)
- Mr. Philippe Boucly, President
- Mr. Jean-Paul Reich, Vice-President, Senior Advisor, Hydrogen Specialist and former Scientific Director of ENGIE
- Mr. Maxime Sagot, Head of Institutional Relations

Air Liquide
- Mrs. Geneviève Samson, H2 Global Director for Marketing, Communications and Public Relations
- Mr. Fabrice Delcorso, the Group's global expert on gas and energy production (including hydrogen) and life cycle analyses.
- Mr. Paul-Edouard Niel, French Public Affairs Director

ENGIE
- Mrs. Secil Torun, Head of the CRIGEN "Hydrogen Lab" and ENGIE's greenhouse gas R&D centre (hydrogen, biogas and liquefied gases)
- Mr. Pierre Olivier, Head of Hydrogen Projects at the "Hydrogen Lab"
- Mrs. Mercédès Fauvel-Bantos, Head of Parliamentary Relations

GRTgaz
- Mr. Thierry Trouvé, Managing Director
- Mr Anthony Mazzenga, Director of renewable gas activity
- Mrs. Agnès Boulard, Head of Institutional Relations

EDF – Électricité de France
- Mr. Bernard Salha, R&D Director and Technical Director
- Mrs. Carmen Munoz Dormoy, Director of Downstream Activities
- Mr. Etienne Brière, Director of the Renewable Energy, Storage and Environment Programme
- Mrs. Véronique Loy, Assistant Director of Public Affairs

Hynamics (EDF subsidiary)
- Mrs. Christelle Rouillé, Managing Director

RTE – Réseau de transport d'électricité
- Mr. Thomas Veyrenc, Director of Strategy and Forecasting

Total
- Mrs. Gabrielle Gauthey, Managing Director
- Mr. Pascal Siegwart, Director of Carbon Markets and Economics
- Mr. Adamo Screnci, Director of Green Hydrogen
- Mr. Bruno Seilhan, Director of CCS (Carbon Capture and Storage) projects
- Mr. Jean-Pierre Dath, R&D Manager
- Mr. Stéphane Raillard, Hydrogen R&D Manager
- Ms Claire Mirian, Policy Officer

Genvia
Mrs. Florence Lambert, President and CEO, and former Director of CEA-Liten

McPhy
- Mr. Laurent Michel, Managing Director
- Mr. Gilles Cachot, Deputy Managing Director and Director of Operations

Elogen (formerly Areva H2Gen)
- Mr. Jean-Baptiste Choimet, Managing Director and Chief Operating Officer
- Mr. Fabien Auprêtre, Project Manager
- Mr. Pierre Millet, Director of Innovation
- Mr. Jean-Marc Leroy, Sales Manager

Sylfen
Mr. Nicolas Bardi, President

Haffner Energy
Mr Philippe Haffner, President
- Mrs. Fabienne Herlaut, Managing Director

Advisors and lawyers

- Mr. Claude Heller, international hydrogen advisor (former director of R&D programmes at Air Liquide)
- Mrs. Sophie Pignon, Partner at Taylor Wessing
- Mrs. Noëlène Grenard, lawyer