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Hydrogen today and tomorrow

Marc Fontecave, Sébastien Candel, Thierry Poinot

► **To cite this version:**

Marc Fontecave, Sébastien Candel, Thierry Poinot. Hydrogen today and tomorrow. Académie des sciences (France). 2024. hal-04678172

HAL Id: hal-04678172

<https://hal.science/hal-04678172v1>

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ACADÉMIE
DES SCIENCES
INSTITUT DE FRANCE

Report by the French Academy of Sciences
April 9, 2024

Hydrogen today and tomorrow



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EXECUTIVE SUMMARY

The prospects offered by hydrogen as part of the energy transition and the decarbonization of the energy system are major topical issues. Although sources of natural hydrogen have been identified in various parts of the world, it is not possible to estimate at this time the potential of these sources, nor to assess their exploitation capacities without further exploration. Thus, hydrogen is not a primary energy source but should only be considered as an energy carrier. Most of this hydrogen, produced today from fossil resources mainly for industrial usage (including oil refining and ammonia synthesis), will have to be obtained tomorrow from decarbonized processes and used more widely for other industrial applications (notably to reduce the carbon footprint of steel and cement production) and for heavy mobility. Given that hydrogen production must be guided primarily by the need to reduce greenhouse gas emissions, this report aims to define what is meant by "decarbonized" hydrogen, which must take precedence over all carbon-based hydrogen. The aim of this report is to clarify how hydrogen can be produced with minimal emissions of greenhouse gases, consider the significant needs it will generate in terms of electrical energy production¹, on this basis identify the most appropriate uses for it in the future and derive estimates of a reasonable level of hydrogen production and consumption.

The production of hydrogen by water electrolysis, which appears to be a key element in terms of carbon dioxide emissions (CO₂), is really decarbonized if the electricity employed for its production is low carbon (nuclear or renewable), which is far from being the case in Europe or at a worldwide level. For the time being, the European electricity mix is largely carbon-based, and its use to power electrolyzers would lead to CO₂ emissions twice as high as those of the conventional methane synthesis process. With its remarkably low carbon electricity mix, France has a major asset in playing a pioneering role in the deployment of low carbon hydrogen, provided that the new electricity production capacities required are rapidly available and themselves low carbon.

The present analysis underlines the importance of the industrial competitiveness challenge of developing electrolyzers with the highest possible performance, in the service of national energy sovereignty. Efforts in this field deserve to be supported by scientific and technological research into the energy efficiency of electrolyzers and fuel cells, issues relating to reducing the environmental footprint of these components, improving their stability and lifespan, and, more generally, all the elements in the value chain (tanks, new materials, materials and molecules for storing and transporting hydrogen, etc.). The report also highlights the need to guide choices and developments through life-cycle analyses carried out across the entire value chain. The safety issues in using hydrogen are of major importance. New scientific and technological knowledge is essential if one wishes to define safe hydrogen applications. For applications envisaged outside industrial areas, one has to ensure that protocols and regulations remain compatible with their dissemination.

Analysis of the future uses of carbon-free hydrogen indicates that, applications should initially be mainly in: (i) the industrial field, essentially to defossilize the industrial processes that emit the largest amounts of greenhouse gases (notably steel and cement production) and to replace grey hydrogen in current industrial uses (synthesis of ammonia and methanol); (ii) the field of heavy transport (sea or air), notably by enabling the synthesis of alternative fuels to replace current fossil fuels.

¹. Considering current electrolysis yields, the production of 1 million tons (Mt) of hydrogen, containing 33 TWh of energy, requires around 55 TWh of electricity.

Hydrogen in a few key facts and figures.

Current production and consumption in France are around **0.9 million tons (Mt)** of hydrogen per year. As elsewhere in the world, this corresponds to grey hydrogen, produced from the reforming of natural gas. It is mainly used for petroleum refining and ammonia synthesis (necessary for fertilizer production).

To produce 1Mt of green hydrogen (by electrolysis of water with decarbonized electricity) one needs **55 TWh**, i.e. the annual output of **5 EPR of 1 600 MW**.

Hydrogen consumption for current industrial uses in France will diminish (notably with the decline in refining), but new uses for "green" steel and cement production call for a demand of 1.6 Mt. If one adds the demand for synthetic liquid fuels for the heaviest forms of transport (sea and air), the demand by 2050 could be **4 Mt**, the upper limit of all scenarios, requiring **230 TWh** of dedicated power generation.

At the European level, a consumption of **60 Mt** of green hydrogen is envisaged **by 2050**, 50% of which would be produced in Europe, thanks to 300 GW of electrolysis capacity and the production/consumption of around 1,700 TWh of low carbon electricity. The additional 30 Mt of hydrogen would be imported. As current grey hydrogen production is 10 Mt, this forecast appears to be significantly overestimated.

Hydrogen produced with electricity from the European grid would induce emissions of 20 kg CO₂/kg H₂, i.e. twice the value corresponding to grey hydrogen. Not all hydrogen produced by electrolysis can be called green hydrogen. The level of CO₂ emissions can be very low (<1 kg eqCO₂/kg H₂) if the electricity is of nuclear, wind or hydraulic origin. **France, with its highly decarbonized electricity production**, can produce hydrogen by electrolysis, emitting only around 2 kg eq CO₂ / kg H₂.

Reducing the production price of green hydrogen is a major objective. At present, **this price is between €4 and €8/kg green H₂ depending on the technology**, compared with €1.5-2/kg grey H₂. For hydrogen to play a significant role in the energy system of the future, one has to be able to **to bring back this price below €3/kg H₂**.

Introduction.

Hydrogen has long been the subject of both hopes and fantasies.

Hopes are pinned on the uniqueness of this fuel, which is rich in energy that can be released without carbon dioxide emissions (CO₂), leading to the prospect of its large-scale use for the defossilization of a wide range of uses (transport, industrial processes, and electrical flexibility) in tomorrow's energy system.

Fantasies are fueled by the regular promise of the imminent advent of a hydrogen society, where this fuel would replace all others. But it must be said that this society is likely to be a long time coming. These fantasies also stem from an unfortunately frequent confusion between energy source and energy carrier. The term "energy source" refers to energy that can be described as primary, i.e. naturally available, and directly usable. This is the case for fossil fuels (coal, oil, natural gas), uranium, wind, biomass, solar radiation, geothermal energy, and waste. Hydrogen itself can be a source of energy: as will be explained later in this report, we now know that there are natural production sites for this gas in many parts of the world. However, it is still too early to say whether these natural resources of hydrogen, described as "white" hydrogen, will be sufficient and whether they will be exploitable. This explains why, for the time being, the decarbonized hydrogen mentioned in all scenarios is produced by electrolysis of water. It therefore does not have the characteristics of an energy source but corresponds to a "secondary energy" or an "energy carrier", i.e. a form of energy obtained by transforming another form of energy (chemical or electrical, for example), and convertible, itself, into another form of energy² (heat or electricity, for example). Note

that production and conversion are never carried out with 100% efficiency: the energy contained in the hydrogen thus formed and exploitable is only a small fraction of the energy that had to be expended to produce it.

These hopes and fantasies go back a long way. Take, for example, Jules Verne's *Mysterious Island* (1875), in which Cyrus Smith is asked, "*And what will we burn instead of coal? "Water! Yes, my friends, I believe that water will one day be used as a fuel, that the hydrogen and oxygen which constitute it, used singly or simultaneously, will provide an inexhaustible source of heat and light of an intensity that coal could never have... So, nothing to fear"*³.

Today, this enthusiasm is stronger than ever, and has unfortunately led some hydrogen promoters to make inaccurate claims and unrealistic forecasts, which have already been disproved. The title of the emblematic "Hydrogen, the new oil" is clearly misleading, as we have just pointed out⁴.

Alongside these unreasonable documents, one also finds comprehensive and up-to-date reports on hydrogen⁵. They provide a better understanding of the role that hydrogen could play in tomorrow's energy system, the uses in which its deployment is relevant, and the inescapable physicochemical and economic limits to its use⁶. Thus, based on the available bibliography, the aim of the present report is to take stock of a certain number of scientific and technical data essential for guiding the recommendations needed to define a reasonable place for hydrogen in the future energy mix, particularly as far as France is concerned. To give an international perspective, an insert summarizes the main lines of hydrogen policies in several European countries⁷.

². Electricity is itself an energy carrier. It exists only through the conversion of primary energy.

³. Obviously, water is even less of a source of energy! But it is important to understand that water, composed of bonded hydrogen and oxygen atoms, can be transformed into molecular hydrogen and oxygen, at the cost, of course, of energy consumption. This is "green" hydrogen, which will be discussed at length in this report.

⁴. Adapted from Lepercq T. *Hydrogen, the new oil*. 2019. *Éditions le Cherche Midi*. Note that some of the many prophecies have already been disproved, such as "Clean hydrogen, a credible alternative to fossil fuels as early as 2020?" (p. 165); "From 2024 onwards, the strategic horizon for H₂ takes on a different dimension: the aim is nothing less than to compete on a large scale with oil, gas and coal by achieving equivalent or even lower prices." (p. 171). The year is 2024 and none of this has happened.

⁵. See the [bibliography](#) included in this report.

⁶. See, for example: EDF R&D. *Decarbonated hydrogen*. 2019. *Les éditions Lavoisier*, Paris ; French Academy of Technologies. [The role of hydrogen in a decarbonized economy. 2020](#). ; Le vecteur Hydrogène-2021- Foresight Committee of the French Energy Regulatory Commission.

⁷. See insert "[Overview of hydrogen policies in several European countries](#)".

1. Hydrogen: current situation and outlook to 2050 in France, Europe, and the rest of the world.

Most of today's national and European energy policies foresee a very high production and use of hydrogen, well above current levels. However, to be de-fossilized, this hydrogen needs to be "green"⁸, i.e. produced by electrolysis of water using renewable electricity (solar and wind power, for example), or "yellow", if it is produced from electricity of nuclear origin, one of the synthesis processes that emits the least amounts of CO₂⁹.

Today, the hydrogen available is "grey", i.e. over 99% produced from fossil resources. Methane, for example, can be converted into hydrogen by a process known as steam reforming. Synthesis processes of this type emit significant quantities of CO₂ but are still by far the most economical¹⁰. To meet greenhouse gas (GHG) emission reduction targets, one therefore needs to either phase out these processes as quickly as possible or install means for capturing and sequestering the CO₂ emitted by these reactors. However, this second option is highly ambitious: the capture and sequestration of CO₂, which is often evoked as a way of continuing to use steam methane reforming, raises considerable technical problems in terms of implementation and large-scale deployment, even though this technology has reached a significant degree of maturity.

Hydrogen in France.

France currently produces and consumes around 0.9 Mt of hydrogen per year. As elsewhere in the world, this is grey hydrogen, used mainly for petroleum refining, ammonia synthesis (essential for fertilizer production), and in a variety of chemical industry processes, such as methanol

production (Figure 1). This use of hydrogen, mainly for industrial purposes, is responsible for 2.5% of total CO₂ emissions and 7.5% of CO₂ emissions from the industrial sector.

The French government is providing massive support for the hydrogen industry, notably through the "France 2030" plan, with 9 billion euros to be spent by 2030, in addition to the 2 billion euros spent between 2020 and 2022. The aim is to replace grey hydrogen with green/yellow hydrogen in current applications, to de-fossilize the industry and enable new uses, notably in heavy mobility (buses, trains, planes). The relevance of this ambition is undeniable for a country like France, which can already rely on highly decarbonized electricity and plans to maintain a high level of nuclear power generation, particularly virtuous in terms of carbon footprint. This policy translates into support for:

- The development of an industrial electrolyzer sector, with a capacity of 6.5 GW to produce 0.6 Mt of carbon-free hydrogen per year by 2030, and 10 GW in 2035 corresponding to 1 Mt of carbon-free hydrogen¹¹.
- Research, to optimize green/yellow hydrogen production and conversion technologies and reduce hydrogen production costs, which are still too high.

Annual hydrogen consumption up to 2050 is the subject of a wide variety of scenarios, ranging from 1 Mt of green/yellow hydrogen (*Stratégie nationale Bas Carbone* - SNBC- and RTE's 2020 "scénario de référence"¹²) to 3.9 Mt (RTE's "trajectoire hydrogène +" scenario¹³). The higher values correspond to scenarios in which significant quantities of hydrogen would be used for road and air transport (notably to produce synthetic liquid fuels) and for power system flexibility¹⁴.

⁸. Hydrogen is defined by colors according to its mode of production, as will be seen later.

⁹. Depending on the low carbon electricity source used, 1 to 3 million tones (Mt) of CO₂ are emitted to produce 1 Mt of hydrogen by electrolysis.

¹⁰. Around 10 Mt of CO₂ are emitted to produce 1 Mt of hydrogen by steam reforming.

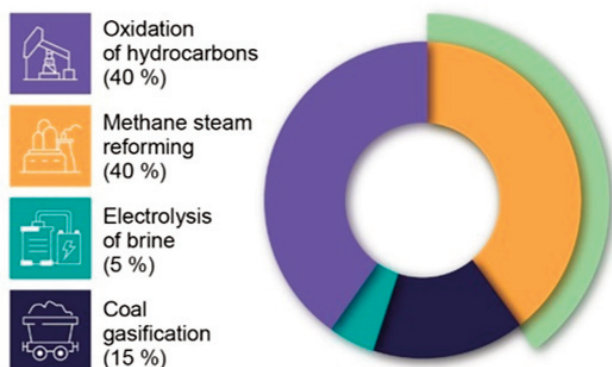
¹¹. Assuming a load factor of around 60% and an electrolyzer efficiency of 60%.

¹². RTE. The transition to low carbon hydrogen. 2020. [Link](#); RTE. Energy futures. 2021. [Link](#); RTE. Chapter 9: the role of hydrogen and coupling.

¹³. *Ibid*.

¹⁴. This is the power-to-hydrogen-to-power strategy, which stores excess low carbon electricity (when production exceeds consumption) in the form of hydrogen produced by water electrolysis, and supplies electrical energy when consumption exceeds production, by oxidation/combustion of the stored hydrogen.

Hydrogen production



Hydrogen consumption

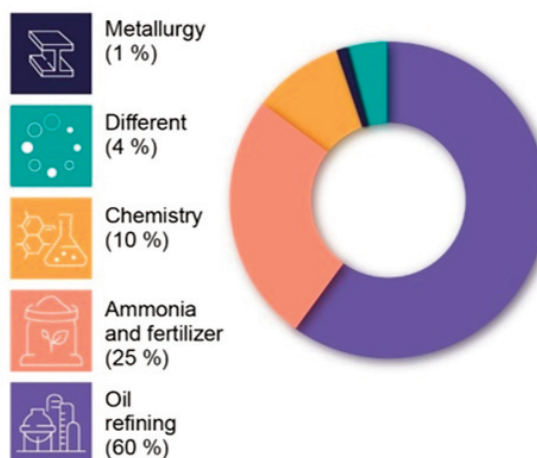


Figure 1. Hydrogen production and consumption in France. Source RTE.

However, there is every indication that the targets set will not be met¹⁵. At the end of 2023, installed capacity was just about 0.03 GW, a far cry from the 6.5 GW set for 2030 (just 0.5% of this target). Considering projects under construction or having received a final investment decision, 0.3 GW of capacity might be reached (5% of the target)¹⁶ and this level places France third in Europe¹⁷.

There are several reasons for the slowness of this momentum: (i) The long time it takes Europe to process applications for state aid; (ii) Problems with the reliability and life duration of electrolyzers; and (iii) Insufficient demand due to the cost of electrolytic hydrogen¹⁸.

Hydrogen in Europe¹⁹.

The European Union (EU), particularly under pressure from Germany, which sees green hydrogen as a major tool to defossilize its energy

and reduce its dependence on Russian gas, is aiming for rapid growth in the use of hydrogen, notably through the Green Pact for Industry²⁰. However, the colossal figures proposed for 2050 are unrealistic. While European consumption is currently around 10 Mt of hydrogen, mainly grey, the level envisaged for 2050 is 60 Mt of green/yellow hydrogen, 50% of which would be produced in Europe, thanks to an installed electrolyzer capacity of 300 GW and a total amount of 1,700 TWh²¹ of low carbon electricity for electrolysis²². The additional 30 Mt would be imported from non-EU countries, such as those in North Africa (Morocco or Algeria), the Middle East or the Persian Gulf (Saudi Arabia), which have unique potential for solar power generation. This scenario obviously requires the installation of electrolysis capacities in these countries, as well as hydrogen transportation infrastructures²³, all of which do not currently exist²⁴.

¹⁵. France Hydrogen Association. Hydrogen deployment barometer, January 2024.

¹⁶. With 0.2 GW for a single electrolyzer; project for the largest electrolyzer in the world, supported by Air Liquide.

¹⁷. After Sweden (1,397 MW) and Germany (567 MW).

¹⁸. 70-80% of this cost is determined by the price of electricity. Producers consider that the price of electricity should fall to €40/MWh, well below the current price of electricity to allow a competitive offer of green hydrogen.

¹⁹. See Box 1 "[Overview of hydrogen policies in several European countries](#)" for more information on this subject.

²⁰. REPowerEU (2020) and Net-Zero Industry plans.

²¹. This represents a 63% increase with respect to current EU electricity consumption of 2,700 TWh.

²². Considering present electrolysis yields, 1 Mt of hydrogen requires around 55 TWh of electricity, so for 30 Mt one needs 1650-1700 TWh. What's more, the figure of 1,700 TWh corresponds to 60% of European electricity consumption, which today stands at 2,800 TWh/year, requiring the massive installation of new low carbon power generation capacity to produce these 30 Mt of green/yellow hydrogen. Finally, considering that 4% of today's hydrogen is produced by electrolysis (i.e. 0.4 Mt), going to 30 Mt means multiplying electrolytic hydrogen production by a factor of 80 in 25 years!

²³. Transportation can be by pipeline (hydrogen) or by ship (e.g. after transformation of hydrogen into ammonia).

²⁴. 30 Mt corresponds to the volumes of gas currently imported, but with 2/3 less energy, due to the difference in volumetric energy density between methane and hydrogen.

This need for imports is partly due to the shutdown of nuclear power plants in some major EU countries, such as Germany and Belgium, and the impossibility of generating the necessary electricity from solar and wind farms alone. It should be noted, however, that this policy effectively replaces dependence on fossil fuels with a new dependence on hydrogen. The latter is particularly problematic when one considers the unstable geopolitical context of the countries where hydrogen is supposed to be produced or through which it is supposed to be transported. Moreover, this policy might be depicted as a new kind of colonialism.

The corresponding energy dependence, and the scale of the infrastructure (pipelines and hydrogen-carrying ships) required to create this new commercial network, are all sources of fragility for importing countries, and underline the need for sovereign hydrogen production policies, such as the one being pursued by France²⁵.

Hydrogen worldwide.

Today, global hydrogen consumption is in the order of 95-100 Mt. Less than 0.1% of this originates from low carbon energies, which explains why it is responsible for 2.5% of global CO₂ emissions (around 1 gigaton (Gt)).

In its Net Zero Emissions (NZE) scenario, the International Energy Agency (IEA) forecasts consumption of about 500 Mt of hydrogen by 2050, including 320 Mt of green/yellow hydrogen. This corresponds to an increase of at least a factor of 3,000 compared with what is currently produced from low carbon energies, which seems unrealistic. The remainder would be produced from fossil fuels, with capture of the CO₂ emitted²⁶.

²⁵. See insert "[Overview of hydrogen policies in several European countries](#)".

²⁶. Castelvechi D. How the hydrogen revolution can help save the planet. *Nature*. 2022. **611**, 440-443.

Box 1²⁷: Overview of hydrogen policies in several European countries.

Almost everywhere in Europe, there is renewed interest in the production and consumption of carbon-free hydrogen. Hydrogen is a major component of strategies to decarbonize energy systems and the energy-consuming sectors: industrial processes, heating, and transport. In July 2020, the European Commission published its hydrogen strategy. Since then, many European countries have disclosed their national roadmaps, targets, and investment forecasts, most often looking ahead to 2030.

The following summarizes the main data available in an article published in 2021 in the *Revue de l'énergie*, as a follow-up to a study carried out by members of the World Energy Council's European region²⁸.

An initial objective for many countries is to install significant electrolysis capacity by 2030 (Table E-1).

	Roadmap/strategy	Electrolyser capacity objective in 2030 [GW]	Date of publication
France	(FR Gov, 2020b)	6.5	Sept. 2020
Germany	(BMWi, 2020a)	5	June 2020
Italy	(MISE, 2020)	5	Nov. 2020
Spain	(MITECOB, 2020)	4	July 2020
Netherlands	(NL Gov, 2020)	3-4	April 2020
Sweden	–	3 ¹	To be published
Portugal	(PT Gov, 2020)	2-2.5	August 2020
Belgium	–	2.2 ²	To be published
Poland	(PL MKiS, 2021)	2	Draft
European Union	(CE, 2020a)	40	July 2020

1. The roadmap is currently being prepared. The estimate comes from the Fossil Free Sweden initiative.

2. The estimate is cited in the FCH JU study, 2019, the roadmap has not yet been published.

Table E-1. Roadmaps and 2030 targets for several European countries.

Despite these efforts, the complete decarbonization of hydrogen is not expected until 2050, and a significant proportion (>80%) of hydrogen demand in Europe will be grey hydrogen (or, very marginally, blue, if some existing steam reforming plants are upgraded with CO₂ capture equipment) (Figure E-1).

Policies are aligned in the effort to simultaneously develop production and demand for decarbonized hydrogen according to two options:

- (1) By creating "hydrogen valleys" where demand from energy-intensive industries, production capacities and local infrastructures are developed.
- (2) By setting a level of hydrogen/gas mixing in gas networks, as is done in some roadmaps, despite a series of major drawbacks for this route: (i) A limit on hydrogen concentration (< 10%) due to technical tolerance problems; (ii) A resulting depletion of the energy content density of the gaseous mixture²⁹.

²⁷. *La Revue de l'Énergie*. Decarbonized hydrogen imports into the European Union: challenges and opportunities. October 2021. All figures in this insert are from this publication.

²⁸. *Ibid.*

²⁹. The volumetric energy density of hydrogen is lower than that of methane, the main component of natural gas.

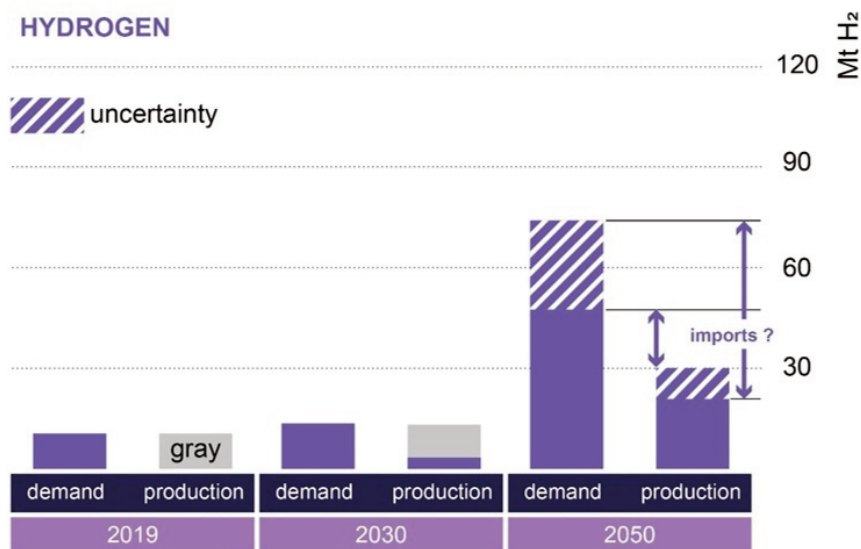


Figure E-1³⁰. Hydrogen demand and production in the EU 2019-2030-2050. Decarbonized hydrogen in purple; gray hydrogen in gray.

The most apparent difference between European countries lies in the gap between production and demand (Table E-2).

[Mt H ₂]	2019	2030		2050		Imports [%]
	Demand	Demand	Production	Demand	Production	
Austria	0.1	0.2	0.1	0.6 – 1.5	0.2 – 0.4	63% – 71%
Belgium	0.9	1.1	0.1	2.8 – 3.3	1.8 – 2	35% – 39%
France	0.9	1.0	1.0	1.1 – 4.5	1.8 – 4	-60% – 12%
Germany	1.6	3.3	0.4	11 – 21	3.2 – 5.5	72% – 74%
Italy	0.5	0.7	0.2	6 – 8	2.2 – 2.6	64% – 67%
Netherlands	1.5	1.7	0.2	3.9 – 4.7	2.6 – 3	33% – 36%
Poland	1.0	1.1	0.1	3.6 – 4	1.5 – 1.8	58% – 56%
Spain	0.5	0.6	0.2	2.6 – 3.5	2.9 – 3.9	-12% – -11%
Other EUs	3.1	3.5	0.4	8 – 9.5	5.1 – 6.3	36% – 33%
Total EU	10.1	13.2	2.6	40 – 60	21.3 – 29.6	47% – 51%

Table E-2. Hydrogen supply and demand in the EU according to high hydrogen demand scenarios, 2019-2030-2050.

Notes: hydrogen demand in 2019 and 2030 is met by both carbon-intensive and decarbonized hydrogen production. Hydrogen demand in 2030 only includes production from electrolyzers running on decarbonized electrical sources, while all hydrogen produced in 2050 is decarbonized. The figures gathered in this table do not consider any EU-wide blending obligations. Negative import figures represent exports..

³⁰. IEA sustainable development scenario. *La Revue de l'Énergie*. Decarbonized hydrogen imports into the European Union: challenges and opportunities. October 2021

Most European countries (Germany, Belgium, Italy, the Netherlands, Poland) are projecting their demand for hydrogen at a much higher level than the quantities produced, and the balance between supply and demand can only be ensured by resorting to massive imports of green hydrogen, from origins that are not easy to figure out. France and Spain are the only countries having roadmaps that call for a balance and even, in some scenarios, an excess of hydrogen generation enabling exports to countries where demand exceeds production.

Hydrogen production costs are comparable from one country to another by 2050, with the highest costs (around €3/kg) for electrolysis assisted by onshore wind power and the lowest (€1.4/kg) with photovoltaics in Spain (Table E-3).

		Gas based				Electrolysis							
		Methane steam reforming with CUSC		Pyrolysis		Onshore wind		Offshore wind		Photo-voltaic fields		Nuclear	
		2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Austria	\$/MWh	54	55	87	76	118	90	n.d.	n.d.	136	80	n.d.	n.d.
	\$/kgH ₂	1.8	1.8	2.9	2.5	3.9	3.0	n.d.	n.d.	4.5	2.7	n.d.	n.d.
France	\$/MWh	54	55	85	72	113	87	109	71	116	70	54	69
	\$/kgH ₂	1.8	1.8	2.8	2.4	3.8	2.9	3.6	2.4	3.9	2.3	1.8	2.3
Germany	\$/MWh	54	55	87	78	118	90	100	65	148	87	n.d.	n.d.
	\$/kgH ₂	1.8	1.8	2.9	2.6	3.9	3.0	3.3	2.2	4.9	2.9	n.d.	n.d.
Italy	\$/MWh	54	55	89	80	132	100	n.d.	79	90	55	n.d.	n.d.
	\$/kgH ₂	1.8	1.8	3.0	2.7	4.4	3.4	n.d.	2.6	3.0	1.8	n.d.	n.d.
Spain	\$/MWh	54	55	87	74	109	84	111	76	81	41	n.d.	n.d.
	\$/kgH ₂	1.8	1.8	2.9	2.5	3.7	2.8	3.7	2.5	2.7	1.4	n.d.	n.d.

Table E-3. Hydrogen production costs for various countries up to 2050.

Notes: these results do not include transportation costs. All calculations are based on average capital costs (around \$400/kW in 2050) and not on the cheapest available (\$160/kW), to reflect the average cost of production. For nuclear power in France, the production cost of hydrogen is lower than that which would use electricity generated by new nuclear plants, as the calculation only considers the additional production obtained by increasing the utilization rate of existing power plants.

The article³¹ concludes with a chapter entitled "Country profiles", providing key figures for Austria, France, Germany, Italy, and Spain.

³¹. *La Revue de l'Énergie*. Decarbonized hydrogen imports into the European Union: challenges and opportunities. October 2021.

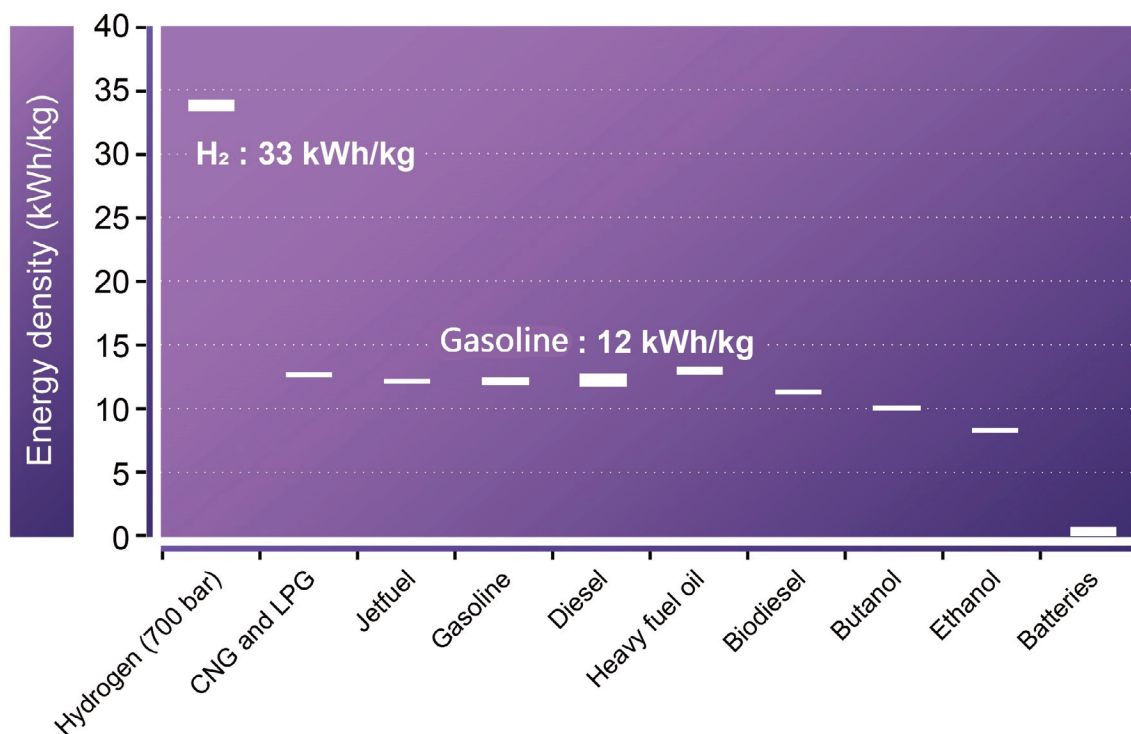


Figure 2. Energy densities per unit mass.

2. Hydrogen: physicochemical characteristics and implications for transport and storage.

Hydrogen, in the dihydrogen form H_2 , is an energy-rich molecule, contained in the bond between the two hydrogen atoms. Its energy density per unit mass is 33 kWh/kg (or 120 MJ/kg), i.e. 2.7 times that of oil, 2.4 times that of gas and 5 times that of coal (Figure 2). Unfortunately, the density of gaseous hydrogen is low. With a density of 0.09 g/L at atmospheric pressure and ambient temperature, 1 kg of hydrogen, containing 33 kWh of energy, occupies a volume of 11,000 liters (11 m³), at atmospheric pressure, when the same energy is contained in 3.6 liters of liquid petroleum³².

This has a major consequence: the large-scale use of hydrogen, its storage and transportation require that its volume be reduced to a

maximum. This is made possible by various processes, some of which are already mature while others still require research and development.

A considerable reduction in volume can be achieved by commonly used physical processes. Firstly, liquefaction: when hydrogen is stored in liquid form at very low temperatures (-253°C or 20 K), its density in this state reaches 70 g/L. Secondly, compression at pressures of 350 or 700 bar yields densities of 23 and 29 g/L respectively³³.

These physical transformations are energy-intensive³⁴. Furthermore, the storage and transportation of hydrogen in these less voluminous forms requires design and engineering of specific tanks or containers, to avoid leaks³⁵ and the development of original materials (metals, composite materials based on carbon fibers and polymers, etc.).

³². 1 liter of oil contains the same energy as 2,750 liters of hydrogen gas.

³³. As a result, 1 kg of hydrogen (i.e. 33 kWh), which occupies a volume of 11,000 liters in the gaseous state, takes the form of a volume of 13.6 liters in the liquid state or 23.3 liters in the gaseous state under a pressure of 700 bar

³⁴. Liquefying one kg of hydrogen consumes 11.6 kWh (35% of its energy content) while compressing one kg of hydrogen consumes 4.9 kWh (15% of its energy content).

³⁵. The lightness and small size of hydrogen molecules enable them to rapidly diffuse through air, but also through solids.

Chemical processes can also be envisaged to reduce volume, are much less mature, but the subject of intense research. These processes exploit various types of materials capable of fixing and accumulating hydrogen molecules within them, then releasing them under reasonable temperature and pressure conditions. These can include porous materials (carbonaceous materials, zeolites, Metal Organic Frameworks (MOFs), etc.) that reversibly fix hydrogen molecules by physisorption onto pore surfaces via weak bonds, enabling appropriate adsorption/desorption kinetics. Gravimetric capacities more than 6%³⁶ by weight or volumetric capacities of more than 40 g H₂/L can scarcely be achieved at present, and then only at very low temperatures, these capacities being by nature temperature-sensitive because the binding energies are low (4-10 kJ/mol H₂) (Figure 3)³⁷.

It is worth noting that the focus on these processes lies, in particular, in their greater safety and lower energy consumption. Finally, one can take advantage of materials that are reactive by chemisorption, leading by reaction with hydrogen to relatively stable hydrides (interstitial hydrides, metal hydrides such as MgH₂, complex hydrides such as NaBH₄, and chemical hydrides such as ammonoborane -also known as borazane - NH₃BH₃). Hydrogen molecules are absorbed/desorbed by dissociation/recombination, implying high activation barriers. Thus, while record capacities (20% by weight and 150 g H₂/L) can be achieved, as in the case of ammonoborane (NH₃BH₃), this is only possible at very high temperatures (above 300°C)³⁸.

These different materials are well suited to stationary hydrogen storage. For the transport (see below), storage, which is also reversible, is

mainly envisaged through transformation into ammonia (NH₃)³⁹, or into organic liquids. The latter, known as Liquid Organic Hydrogen Carriers (LOHC), can store or de-store hydrogen through catalytic hydrogenation and dehydrogenation cycles⁴⁰.

For the time being, even if these strategies are promising, they are still far from industrial maturity: operating temperatures are too high if one wishes to reach the target values⁴¹ (Figure 3) and costs are still too high. The question of storage methods is crucial for the transport of hydrogen and the development of the hydrogen industry. Resolving this issue calls for unfailing support for research into new materials and storage methods.

3. Hydrogen: existing and future production technologies, and the necessary infrastructure.

As already indicated, over 99% of the hydrogen consumed worldwide is produced from fossil fuels. Hydrogen is said to be "black" when it is obtained by coal gasification without the capture of CO₂ emissions, "grey" or "blue" when it is obtained by steam reforming of natural gas⁴², respectively, without or with the capture of CO₂ emissions.

Plans to decarbonize hydrogen production all aim to switch to "green" hydrogen, obtained by electrolysis of water using low carbon electrical energy sources (wind, solar, etc.), by reforming biogas or gasifying biomass. This observation calls for two comments.

Firstly, the use of biogas or biomass to produce hydrogen must be ruled out, given the many uses already expected for biomass and the limits of its

³⁶. Mass percentage or, in other words, gravimetric capacity.

³⁷. Carbon aerogels feature gravimetric capacities of 5.3% at 77 K, but these decrease sharply at higher temperatures (e.g. 0.9% at 298 K). Liu Y, Brown C.M, Neumann D.A. *et al.* Hydrogen Adsorption in MOF-74 Studied by Inelastic Neutron Scattering. *MRS Online Proceedings Library*. 2007. **1041**, 203. <https://doi.org/10.1557/PROC-1041-R02-03>.

³⁸. The corresponding reaction is: NH₃BH₃ (borazane) → 3 H₂ + (NB)_n (the latter is a polymer). The problem with this reaction is that it is not reversible.

³⁹. Thanks to the reaction N₂ + 3H₂ ↔ NH₃ which will be discussed later, in the chapter on hydrogen transport.

⁴⁰. For example, toluene can be hydrogenated to methylcyclohexane at pressures (30 bar) and relatively low temperatures (90-150°C). Here again, the problem is that the reverse reaction, dehydrogenation, which releases hydrogen, requires a lot of energy and therefore high temperatures (>300°C). Preuster P, Papp C, and Wasserscheid P. Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy. *Acc. Chem. Res.* 2017. **50**, 1, 74-85.

⁴¹. The US Department of Energy (DOE) sets gravimetric capacities of 10 to 20% by weight and volumetric capacities of 60 to 150 g H₂/L at room temperature as targets - see figure 3.

⁴². High-temperature catalytic reaction: CH₄ + 2 H₂O → CO₂ + 4 H₂. This process emits 10 kg of CO₂ per kg of hydrogen produced.

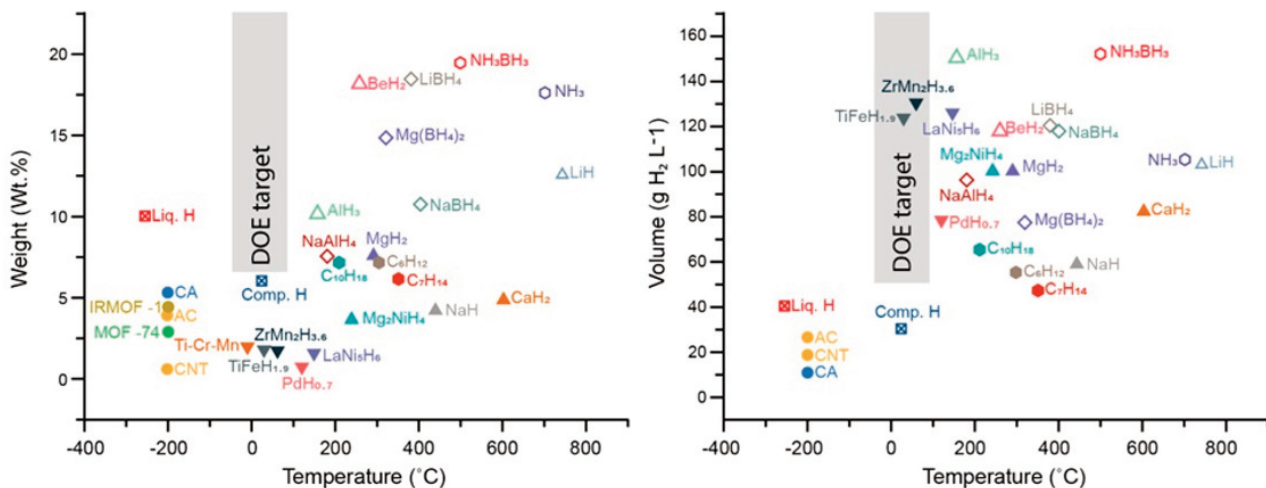


Figure 3⁴³. Gravimetric capacity (% by mass) and volumetric capacity (g H₂.L⁻¹) of different hydrogen storage materials. DOE target: temperature and capacity target ranges set by the US Department of Energy (DOE).

exploitation (competition with agrifood production and insufficient resources in particular), as the French Academy of Sciences' Energy Foresight Committee has just analyzed in a recent report⁴⁴.

Secondly, it is important to stress that all low carbon energies must be mobilized to make hydrogen "green" and a major vector for decarbonization in France and Europe. This necessarily includes nuclear power, a low carbon energy par excellence. Thus, the distinction between "green" hydrogen (produced exclusively from renewable electricity⁴⁵) and "yellow" hydrogen (also produced by electrolysis of water but including nuclear energy as a low carbon energy source) is not operational. In fact, whether hydrogen is "green" or "yellow", it comes from the same synthesis process: water electrolysis. This distinction is unique to Europe, and merely reflects the recurring conflict between pro- and anti-nuclear countries within it. In the remainder of this report, in a logic of

simplicity and consistency, the term green hydrogen will refer to any hydrogen produced by water electrolysis, regardless of the low carbon electrical energy used.

To conclude with the colors of hydrogen, one has to mention "turquoise" hydrogen, obtained by pyrolysis of methane without CO₂ emissions⁴⁶, which also has the advantage of being less expensive in energy⁴⁷ but is likely to make only a marginal contribution to overall hydrogen production⁴⁸.

Given that water is a virtually infinite resource, and that the energy to be used can be low carbon, this brief overview reveals that the key technology for the development of a hydrogen industry remains water electrolysis. It should be noted, however, that this technology is very intensive in energy, and for this reason is the focus of attention in many industrial research laboratories⁴⁹. Indeed, although electrolysis has been a well-known process in industry for at least

⁴³. Guan D, Wang B, Zhang, J *et al*. Hydrogen society: from present to future. *Energy Env. Sci.* 2023. **16**, 4926-4943.

⁴⁴. French Academy of Sciences. What energy prospects for biomass? 2024. See [Link](#).

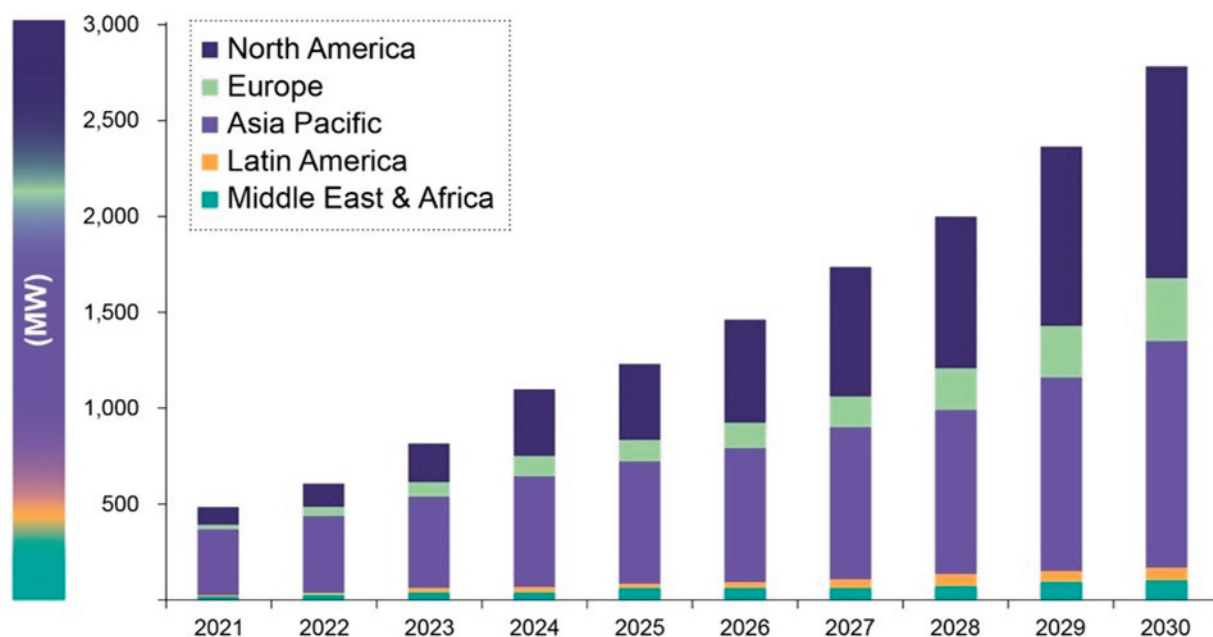
⁴⁵. Ordinance no. 2021-167 of February 17, 2021, on hydrogen. [Link](#).

⁴⁶. This is a high-temperature thermochemical process: CH₄ → 2 H₂ + solid carbon. It produces 3 kg of solid carbon per kg of hydrogen. This carbon can be used as a building material or to amend agricultural soils, but it is not certain that there is a significant market for such a material.

⁴⁷. 10-25 kWh/kg H₂, compared with 55 kWh/kg H₂ green, with today's best yields.

⁴⁸. Research into thermal plasma pyrolysis of methane has been carried out at MINES-ParisTech for over twenty-five years. Fulcheri L. Decarbonated hydrogen production: the third way. *Annales des Mines. Responsabilité et Environnement*. July 2020, n°99. See [link](#).

⁴⁹. Other technologies, notably solar-powered, are also being studied, but are still a long way from reaching the level of maturity required for electrolysis to be commercialized in the short or even medium term, due to insufficient yields and stability, and high costs. They involve coupling semiconductor materials and catalytic materials in the same device, to decompose water directly by exposure to solar radiation. One example is the photolysis of water, first reported in 1972 (Fujishima A. and Honda, K. Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature*. 1972. **238**, 37-38. <https://doi.org/10.1038/238037a0>), or the photoelectrolysis of water in photoelectrolyzers.



(Source: Guidehouse Insights)

Figure 4⁵⁰. Installed electrolyzer capacity 2021-2030.

two centuries⁵¹, water electrolysis is still limited by technological problems, low energy yields and excessive costs.

This explains why, despite massive investments over the last few decades, the contribution of electrolysis to hydrogen production has stagnated at just a few percent in the most developed countries (and remains below 1% globally).

Much remains to be done in terms of research and innovation before green hydrogen production can be deployed on a large scale, from the need to develop new catalytic materials and membranes to improving the energy efficiency and durability of electrolyzers.

Water electrolysis takes place in an electrolyzer coupled to an electrical source which may be the power grid itself, a renewable electricity production source (solar farm, wind farm, hydroelectric power station), or an electricity

production site dedicated to hydrogen production. An electrolyzer consists of two electrodes, each located in a separate compartment. The first is the cathode, on whose surface the catalytic reduction of water to hydrogen takes place, and the second is the anode, on whose surface the oxidation of water to oxygen takes place. Both reactions take place when an electrical source is connected to the electrolyzer. Four types of electrolysis can be distinguished and are gathered in Table 1.

The production of electrolyzers is a major industrial challenge for energy sovereignty, in the same way as the production of batteries and electric cars, or solar panels and wind turbines. This explains the efforts made by the French government and the EU to support a competitive electrolyzer industry. Today, unfortunately, the French situation in this sector is not so favorable and even worrying. World electrolyzer production is essentially dominated by China and the USA, and this situation is likely to persist, as most forward-looking analyses predict (Figure 4).

⁵⁰. GuideHouse Insights. Market Data: Electrolyzers. Clean Hydrogen Production Technologies: Global Market Forecasts and Analysis. 2022.

⁵¹. The first direct-current electrolysis (water electrolysis) was carried out on May 2, 1800, by two British chemists, William Nicholson (1753-1815) and Sir Anthony Carlisle (1768-1842). Brine electrolysis is used industrially to produce chlorine (Cl₂). Hydrogen is recovered as a by-product of the reaction.

Type of electrolysis	Benefits	Limits
Alkaline electrolysis ⁵² The most mature and least expensive technology, in industrial use for a long time.	Uses abundant, inexpensive electrode materials (steel, nickel, etc.).	Low efficiencies (60-65%). Very sensitive to current variations, limiting the possibilities of direct coupling to intermittent electrical sources ⁵³ .
Electrolysis with proton exchange membranes ⁵⁴ This more recent technology has yet to be developed industrially.	Operates at low (ambient) temperatures and is compatible with intermittent power sources.	Numerous drawbacks limit their durability: (i) Polymer membranes, which ensure electrical neutrality, are expensive and fragile; (ii) Acidic environment, responsible for corrosion phenomena, requiring catalysts based on noble metals (platinum and iridium), which are expensive and in short supply; (iii) Energy yields of 65% at best.
High-temperature solid oxide electrolysis ⁵⁵ The least mature technology. The recently created French company Genvia is one of the main players in this field in France and is aiming at offering 1 MW electrolyzers in 2026 (producing 600 kg H ₂ /day).	High temperatures (700-950°C), obtained by coupling with a heat source, significantly improve yields (>80%). Catalysts based on non-noble metals (nickel, metal oxides).	Ceramic membranes adapted to high temperatures remain fragile. The system does not cope well with temperature variations.
Electrolysis with anion exchange membranes (AEM)	Catalysts based on non-noble metals (nickel, metal oxides).	Recent technology, still far from industrial maturity ⁵⁶ .

Table 1. The four types of water electrolysis processes.

4. Green hydrogen: what CO₂ emissions?

The enthusiasm for water electrolysis using low carbon energy sources, instead of steam reforming of natural gas, stems from the possibility of significantly reducing CO₂ emissions associated with hydrogen production. This requires a rigorous and transparent estimate of CO₂ emissions per unit of hydrogen produced, using proven methodologies such as life cycle assessments (LCA). This analysis is necessary across the entire value chain and must consider CO₂ emissions not only when the green hydrogen is used, but also during the production and equipment operation stages, as well as during hydrogen transport and

storage. The contributions of imports associated with the hydrogen sector must also be considered. These various stages account for a significant volume of emissions. However, no global analysis exists to date, and it is important that this gap be quickly filled

It should be noted, however, that several reliable and convergent studies make it possible to quantify the advantage of green hydrogen over grey hydrogen, in terms of GHG emissions during production. It is shown, for example in ADEME's 2020 LCA study⁵⁷, (see Figure 5) that green hydrogen is not "zero-carbon" hydrogen, contrary to popular belief.

⁵². The alkaline character is linked to the fact that the electrolyte is a highly concentrated aqueous potassium solution (KOH 5-7 mol. L⁻¹).

⁵³. There are several reasons for this. One is the inertia of this type of electrolyzer, due to the low mobility of OH⁻ ions in high concentration solutions. The other is linked to the liquid nature of the electrolyte, which makes it difficult to manage temperature and conductivity changes under variable load conditions.

⁵⁴. Proton exchange membrane or PEM.

⁵⁵. Solid Oxide Electrolysis Cells or SOEC.

⁵⁶. The polymer (generally polysulfone) making up the membrane carries cationic functions (quaternary ammonium, phosphonium, etc.) which enable OH⁻ hydroxide ions to be transported. This makes it possible to use less expensive catalysts than in acidic media. Nickel (Ni)-based catalysts are used at the cathode, and iron (Fe), Ni and cobalt (Co) oxides at the anode.

⁵⁷. ADEME. Life cycle assessment of hydrogen. Hydrogen production and use in light mobility. September 2020. See [link](#).

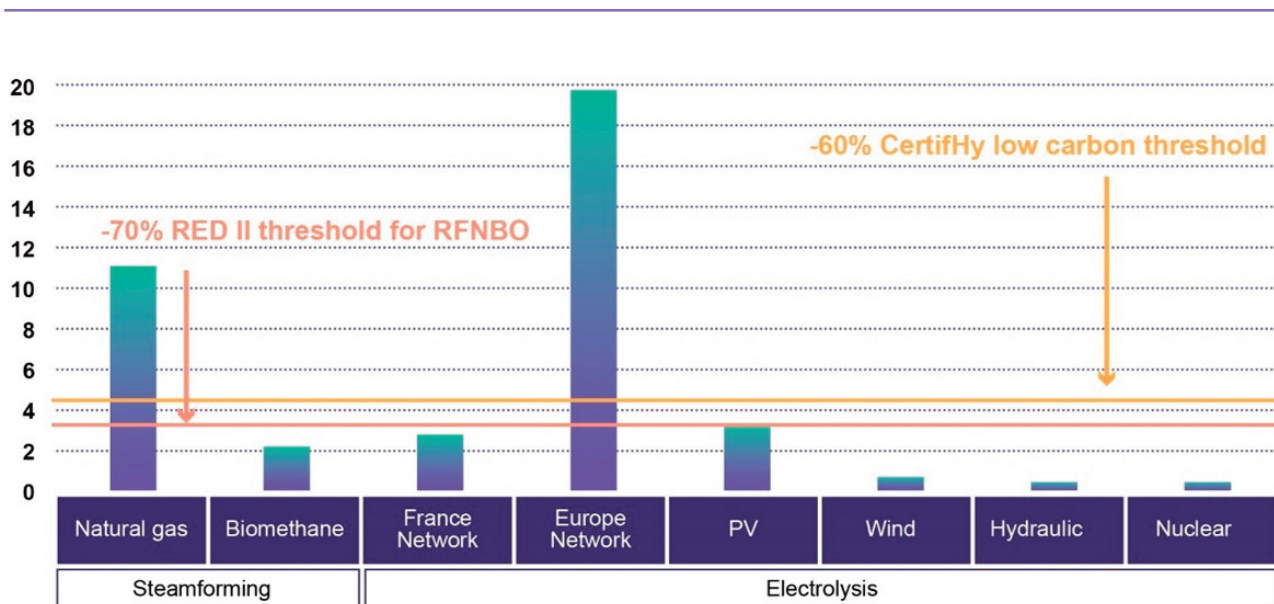


Figure 5⁵⁸. Life cycle assessment of GHG emissions of different means of hydrogen production (in kg eq CO₂/kg H₂)⁵⁹. RFNBO stands for Renewable Fuels of Non-Biological Origin.

Figure 5 shows that the level of CO₂ emissions depends on the carbon footprint of the electrical system. Thus, not all hydrogen produced by electrolysis can be qualified as green hydrogen.

This level can be very low (< 1 kg eqCO₂/kg H₂) using nuclear, wind or hydro power. A country like France, with its highly decarbonized electricity production, can produce hydrogen by electrolysis, emitting only around 2 kg eqCO₂/kg H₂. Conversely, the production of hydrogen by electrolysis in EU countries that massively use coal and gas for electricity generation (Germany, Poland, for example) leads to emission levels (20 kg eqCO₂/kg H₂) that are far greater than those associated with grey hydrogen! Moreover, the various official definitions of green hydrogen do not set the level of GHG emissions at zero⁶⁰.

To understand this, the two thresholds shown in figure 5 are interesting:

- The first, from the European CertifHy28 project, states that any hydrogen with a carbon footprint 60% smaller than that of conventional fossil-gas hydrogen (grey hydrogen) is considered low-carbon.
- The second, defined by the European directive on renewable energies RED II, has imposed a

GHG emissions reduction threshold of 70% compared with grey hydrogen for hydrogen or synthetic fuels to be classified as renewable fuels of non-biological origin⁶¹.

Finally, the delegated act on European taxonomy adopted by the European Commissioners on April 22, 2021⁶² sets emission thresholds for green hydrogen production at 3.0 kg eqCO₂/kg H₂.

5. Natural or native hydrogen: what resources?

The natural hydrogen craze: hype or legitimate hopes?

The emanation of hydrogen gas in many places on the Earth's surface has been known for a long time, so that one may be led to anticipate the presence of large quantities of this gas. This so-called "natural" or "white" hydrogen is particularly interesting because it is obtained as a resource, without any parallel production of CO₂. As a result, native hydrogen has been the subject of a veritable craze in recent years and in many countries, such as Australia and the United States. In France, this has resulted in the granting of a "permit to explore for native hydrogen

⁵⁸. ADEME. Life cycle assessment of hydrogen. Hydrogen production and use in light mobility. September 2020. See [link](#).

⁵⁹. With CO₂ capture, grey hydrogen emissions drop down from 10 to 1.5 kg eqCO₂/kg H₂.

⁶⁰. Sfen. Hydrogen: how nuclear energy can serve France's ambitions. Avis du 28 avril 2021.

⁶¹. Renewable Fuels of Non-Biological Origin (RFNBOs).

⁶². <https://www.actu-environnement.com/media/pdf/news-37409-acte-delegue-taxonomie-climat-ue>.

mines" covering 225 km² in the *Pyrénées Atlantiques* region, with five other projects under consideration⁶³. Another potential deposit, described as "gigantic" and "the biggest in the world", in Lorraine caused quite a stir in the press, including the scientific press⁶⁴, during the summer of 2023. However, one needs to be cautious with announcements of this kind, in the absence of drilling permits and further exploration and at this stage, the term "deposit" is inappropriate⁶⁵.

What we know today about natural hydrogen.

The mechanisms by which natural hydrogen is synthesized are beginning to be understood. These are essentially redox reactions (serpentinization) between rocks containing ferrous iron ores and water. Ferrous ions transfer their electrons to water, producing hydrogen continuously in the earth's crust, at great depths

(1,500 to 3,000m). This reaction is favored by high temperatures (above 150°C). Hydrogen can also be formed by radiolysis and decomposition of water, in sites where natural radioactivity is high. A small molecule that diffuses easily, hydrogen travels rapidly from the sites where it is produced to migrate through faults to the surface, where it can be observed.

This has yet to be evaluated for natural hydrogen.

At present, the exploration experience is not sufficient and the available data are limited and cannot be used to obtain an accurate assessment of the world's potential for natural hydrogen production. Even on the scale of a country like France, such information is not available. In this context, and in the absence of more extensive measurements (requiring drilling permits), caution remains the order of the day.

Box 2: Native hydrogen in the Lorraine Carboniferous Basin.

The discovery of a native hydrogen deposit in Lorraine is the fruit of an R&D project entitled REGALOR for *REssources GAZières de LORraine* covering the period 2018-2023 between the GeoRessources Laboratory (*Université de Lorraine/CNRS*) and *La Française de l'Énergie* with joint funding from the State (*Pacte Lorraine*), the Grand-Est Region and ERDF (European Regional Development Funds). Collaboration between the GeoRessources laboratory and Solexperts, a subcontractor on the REGALOR project, has led to the filing of a European patent relating to the creation of the SysMoG™ probe, the only one of its kind in the world, which enables the measurement of dissolved gases in the water of a deep borehole (up to 1,500 m)⁶⁶. This probe is associated with a field analytical bench based on vibrational, FT-IR and Raman spectroscopy, developed at the GeoRessources laboratory. Estimates of native hydrogen resources cannot be made from surface measurements. This new possibility of obtaining a concentration profile as a function of depth is a breakthrough for such estimation.

The use of this probe has revealed the existence of native hydrogen (white hydrogen) in the subsurface of the Lorraine Carboniferous Basin and established its concentration profile. At a depth of -1,250 m, the hydrogen content expressed as a molar fraction of the gas phase extracted by the probe is of the order of 18%. Applying Henry's law, this corresponds to a dissolved hydrogen content equal to 2.8 mg/L. The linear profile of hydrogen content measured between -600 and -1,250 m, i.e. in the upper part of the Lorraine Carboniferous, suggests a deep⁶⁵ and potentially significant source of hydrogen⁶⁷.

⁶³. French Ministry of Energy Transition. Official Journal of December 3, 2023. [Link](#).

⁶⁴. CNRS le Journal, August 2023. [Link](#).

⁶⁵. According to Larousse dictionary, a deposit is "a place where a given geological material has accumulated and which can be exploited in whole or in part".

⁶⁶. Helmlinger B, Laurent A, de Donato PH, and Pironon J. SysMoG™, Probe for gas analysis in wells at high depth. European Bureau Patent, N° EP22210240.2 - April 2023.

⁶⁷. To date, two hypotheses have been put forward as to the origin of hydrogen in the Lorraine Carboniferous Basin: (1) A redox reaction between water and ferrous carbonates (siderite and ankerite) and (2) Thermal maturation of the coal, and underground transformation from a sub-bituminous state at the top of the Westphalian to anthracite at its base. These two mechanisms are only possible at temperatures above 150 to 200°C, i.e. at a depth of 5 or 6 km, the source of hydrogen being probably located at great depth.

At present, the exploration experience is not sufficient and the available data are limited and cannot be used to obtain an accurate assessment of the world's potential for natural hydrogen production. Even on the scale of a country like France, such information is not available. In this context, and in the absence of more extensive measurements (requiring drilling permits), caution remains the order of the day.

For the moment, there is no serious evidence that this hydrogen, like oil, exists on a massive scale in wells, where it would be accumulated over millions of years. Today, it is essentially “modern” hydrogen from fluxes of recent underground origin which diffuses towards the surface of the Earth.

In some places, however, a significant percentage of helium is found mixed with hydrogen, suggesting that these gases originate from ancient reserves⁶⁸. This question of the existence of flows or stocks of natural hydrogen is decisive, both for the assessment of potential resources and for the methods that could be used to extract this hydrogen.

Finally, it is far too early to say whether this natural resource can be exploited on an industrial scale, and at what cost. Not only does one need to develop the technologies to capture this highly diffusive gas, on the surface or at greater or lesser depths, but one also needs to purify the corresponding gaseous stream. Nevertheless, all the indications are that costs should not exceed those of grey hydrogen, i.e. around €1/kg H₂.

There's no doubt that white hydrogen could open fascinating prospects for the energy transition. However, there is a long way to go before this becomes a reality, the first step being the precise determination of accessible volumes, a key parameter for concluding whether this color of hydrogen will play a role tomorrow in the defossilization of the global energy system.

6. Green hydrogen: what are the limits to its production and use?

Energy-intensive, low-yield hydrogen production.

For the time being, hydrogen is only an energy carrier. Its production by electrolysis of water requires large quantities of electrical energy, some seven times (!) greater than the thermal energy needed to produce it from methane⁶⁹.

It follows that a massive increase in the use of green hydrogen over and above what is consumed today, to levels of at least 1 Mt and up to 4 Mt per year, as proposed in various scenarios for France (SNBC, RTE), can only be effective on condition that new low carbon electricity production capacities (wind and solar farms, and nuclear reactors) are opened in large numbers, and that these installations are operational by 2050.

As already indicated, due to the low efficiency of electrolyzers (excluding high-temperature electrolysis, which is not industrially mature at present), the production of 1 Mt of hydrogen stored at 350 bars, containing an energy of 33 TWh, requires around 55 TWh. To give an order of magnitude⁷⁰, this corresponds to the annual production of 5 EPR-type nuclear reactors or eight and a half current 1 GW nuclear reactors. In its 2020 report, RTE notes that production of 1 Mt of hydrogen by electrolysis is not an electricity generation issue, as the corresponding electricity requirement (around 50 TWh) is equivalent to the amount exported by France in the best years⁷¹. Conversely, producing 4 Mt of green hydrogen (the upper limit of the scenarios) would require 220 TWh of electricity, equivalent to 20 EPR reactors, far more than the number recently requested by the French government from EDF (6 reactors + 8 additional ones). These figures clearly show that it is unrealistic to envisage much more than 1 to 1.5 Mt of green hydrogen by 2050, in a

⁶⁸. One example is the wells located in the Amadeus basin in Australia, where 7 to 8% helium and 4% hydrogen have been found, accumulating over some 500 million years. It would also appear that the hydrogen used in Mali to supply electricity to the nearby village, discovered when drilling for water (100 m deep), came from a reservoir.

⁶⁹. The enthalpy of the reaction $\text{CH}_4 + 2 \text{H}_2\text{O} \rightarrow \text{CO}_2 + 4 \text{H}_2$ is 165 kJ/mol, while that of the reaction $\text{H}_2\text{O} \rightarrow \frac{1}{2} \text{O}_2 + \text{H}_2$ is 285 kJ/mol.

⁷⁰. This is not to say that the response must be exclusively nuclear.

⁷¹. In fact, that's the level of exports we're aiming for in 2023.

context where electrical demand is set to explode to ensure the electrification of transport, heating, power generation and industrial processes. If demand were higher, the only solution would be to meet it with imports from green hydrogen-producing countries, which do not currently exist

The same conclusion can be drawn from a calculation of the electrolyzer power required. The world's largest electrolyzer, developed by Air Liquide in Quebec and now in operation, produces 8 tons of hydrogen per day with a nominal power of 20 MW (PEM technology). An equivalent electrolyzer is due to come on stream in Germany in 2024. There are none in France. To produce 1 Mt, around 350 such units would be needed by 2050, i.e. the commissioning of around 15 installations of this

type per year⁷². It is worth noting that Air Liquide is working on a 200 MW alkaline electrolyzer, although no date has been given for its commissioning

Costly hydrogen production.

The second problem, identified long ago, is the cost of producing green hydrogen. This is obviously a serious economic brake on its industrial development, especially as the difference between the price per kg of green hydrogen and that of grey hydrogen remains high and stable over time (Figure 6). While the latter costs between €1 and €2/kg, the former is on average 4 times higher, ranging from €4 to €8/kg depending on the technology being used⁷³. One may note that around 2/3 of this cost is associated with electricity consumption⁷⁴.

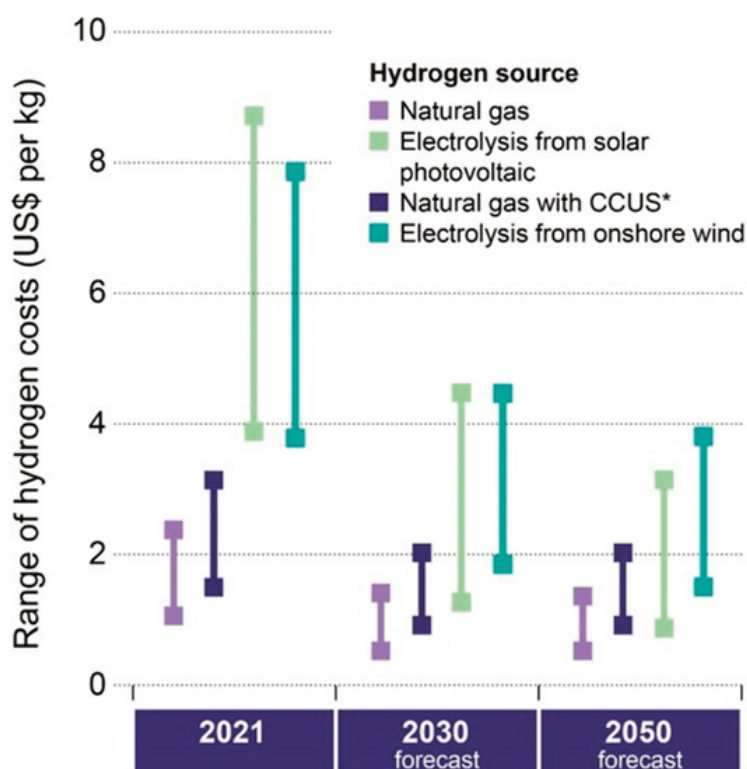


Figure 6⁷⁵. Hydrogen production costs. CCUS stands for "capture, storage and utilization of CO₂".

⁷². For 4 Mt, 1,400 units would be needed! Even if the production of green hydrogen will not depend solely on the use of these large electrolyzers, these figures show that it is unrealistic to set production targets at more than 2 Mt by 2050.

⁷³. Castelvechi D. How the hydrogen revolution can help save the planet - and how it can't. *Nature*. 2022, **611**, 440. These figures converge with those published by ADEME, CRE, OPECST (Parliamentary Office for the Evaluation of Scientific and Technological Options) and RTE.

⁷⁴. Guan D, Wang B, Zhang, J et al. Hydrogen society: from present to future. *Energy Env. Sci*. 2023. **16**, 4926-4943. This result is also based on an electrolyzer energy efficiency of 55 kWh/kg H₂ and an electricity price of €0.1/kWh, giving an electricity cost of €5.5/kg H₂.

⁷⁵. Castelvechi D. How the hydrogen revolution can help save the planet - and how it can't. *Nature*. 2022, **611**, 440.

It is this high cost that explains why demand for decarbonized hydrogen is currently low, demotivating the efforts of potential producers⁷⁶.

Improvements in the energy efficiency of electrolyzers, the development of new electrode materials and membranes, and the effect of scale associated with the installation of a growing number of electrolyzers give reason to hope for a price reduction. Nevertheless, all techno-economic studies seem to show that, despite a net gain, the production cost of green hydrogen should be between €2 and €4.5/kg H₂ by 2050, even if it is difficult to anticipate changes in the price of electricity⁷⁷.

7. Hydrogen: transport and distribution⁷⁸.

What's at stake?

Despite unanimous support for bringing production and consumption sites closer together to limit the costly and complex infrastructure required to transport hydrogen, some countries (particularly in Europe, such as Germany and Belgium) are considering large-scale imports of hydrogen and therefore its large-scale, long-distance transport within or between continents⁷⁹. Furthermore, within a country, distribution between hydrogen stations and individual users requires the implementation of safe, low-cost supply systems. From this point of view, France, with its highly decarbonized electricity grid and controllable sources, has a clear advantage thanks to its production of nuclear and renewable energy (a significant proportion of which is supplied by hydroelectric power), enabling it to locate electrolyzers where hydrogen is being used. Conversely, the situation will be less favorable for countries that have opted to abandon nuclear power (and ultimately fossil fuels) in favor of renewable power generation (wind, solar). Indeed, this production

must be relocated to the most appropriate sites (where there is regular sunshine and wind), which rarely correspond to consumption sites. These countries will thus be faced with an uneven distribution of electricity sources and electrolyzers. For France, the relevant political choice is therefore to favor local production around industrial sites⁸⁰.

The most appropriate transport/distribution strategies.

For long-distance, large-scale transport from producing countries to national terminals in importing countries, pipelines on the one hand, and ammonia, LOHCs and liquid hydrogen on the other, are to be preferred. All these issues are the subject of in-depth technical and economic studies. Economic analyses indicate long-distance transport costs at least comparable to production costs, with intercontinental transport costs higher than continental transport costs⁸¹. For continental transport, hydrogen pipelines appear to be the most economical means, but although projects exist, none are operational. Furthermore, much remains to be done to develop new materials specifically for hydrogen transport, which must combine high resistance to pressure and embrittlement by hydrogen⁸², the ability to prevent leaks and moderate cost. Natural gas pipelines can also be reused, with appropriate adaptations (retrofitted gas pipelines). Finally, hydrogen can also be mixed with natural gas in gas transport networks, but only in limited proportions (<10%) and exclusively for applications in the production of energy or heat by combustion (obviously, this does not mean separating the hydrogen from the gas at the outlet!).

For intercontinental transport, the sea route, in the form of liquid hydrogen itself, or of a liquid hydrogen compound (chemical hydrogen

⁷⁶. A recent CEA study surveying 70 European manufacturers clearly shows that demand today and up to 2030-35 is well above EU production targets, due to high costs, lack of transport infrastructure and a shortage of high-power electrolyzers. See : CEA. Dynamique de la demande européenne en hydrogène bas carbone d'ici 2040 : Étude Sisyphe. See [Link](#).

⁷⁷. Castelvechhi D. How the hydrogen revolution can help save the planet - and how it can't. *Nature*. 2022, **611**, 440 ; Le vecteur Hydrogène-2021- Foresight Committee of the French Energy Regulatory Commission..

⁷⁸. For a full analysis of this topic, see Guan D, Wang B, Zhang, J *et al*. Hydrogen society: from present to future. *Energy Env. Sci*. 2023. **16**, 4926-4943.

⁷⁹. See insert "[Overview of hydrogen policies in several European countries](#)".

⁸⁰. Four hubs have been identified: Fos-sur-Mer, Dunkirk, Le Havre and the chemical valley around Lyon.

⁸¹. Guan D, Wang B, Zhang, J *et al*. Hydrogen society: from present to future. *Energy Env. Sci*. 2023. **16**, 4926-4943.

⁸². Because hydrogen atoms are small, they can permeate solid metals. Once these atoms have been absorbed, the stress required to initiate and propagate a crack is lowered, and the material becomes more brittle: this is known as hydrogen embrittlement.

carrier), as mentioned above, seems to be the most economical. The most emblematic of these compounds is ammonia, obtained by catalytic reaction of hydrogen with nitrogen, in liquid form and storable in tanks⁸³. After transportation and distribution, ammonia must be dehydrogenated ("cracked")⁸⁴ and then purified. This strategy has certain economic advantages, as the capital cost is lower than that of building new pipelines, and the distribution costs lower than those of distributing hydrogen in liquid form. Ammonia has been used in industry for a long time, and the infrastructure for its synthesis has been mastered, amortized and is plentiful. Moreover, ammonia storage and transportation are simple and affordable. Ammonia can be stored in tanks at much higher temperatures than those required for liquid hydrogen (from -33°C to room temperature) and at low pressures (8-10 bar). On the other hand, the energy costs of synthesizing and then dehydrogenating ammonia are not negligible.

The efficiency of the relatively new dehydrogenation process is still insufficient, consuming between 10 and 18% of hydrogen energy. The development of new catalysts and innovative reactors to reduce dehydrogenation temperatures, minimize costs and improve the maturity of the process constitutes a real challenge for research and innovation. The toxicity of ammonia also calls into question the relevance of storing and transporting massive amounts of this compound. It should also be noted that there are currently no ships specifically designed for transporting hydrogen, except for the *Suiso Frontier*, a prototype built by Kawasaki Heavy Industries to transport hydrogen in liquid form⁸⁵.

For short-distance transport and distribution, between hydrogen stations and end users, the best solutions are hydrogen pipeline networks or trucks (with cylinder frames or tanks) carrying

compressed hydrogen or liquid hydrogen, as is done today, the latter ensuring greater throughput.

Hydrogen may be envisaged for decarbonizing rail transport but this possibility is only briefly considered in what follows because rail is already highly electrified in France. One may note that this option is promoted by the French National Rail Company, SNCF, for its non-electrified railroads which represent a significant proportion of the national rail network (nearly 30% of tracks), but with a traffic that accounts for just 11% of the total train-km (the number of kilometers covered by trains) in 2022⁸⁶. Thus, hydrogen will only marginally contribute to rail transport decarbonization⁸⁷.

8. Hydrogen: current and future safety issues related to its use.

The use of hydrogen, outside the industrial context in which it is currently employed with regulated protocols, raises safety issues related to the risk of fires and explosions. The widespread use of batteries to store electricity also raises similar problems, as batteries can generate flammable gases that can cause fires or explosions, while hydrogen can induce scenarios with severe consequences due to the specific properties of this molecule. In 2021, the French *Bureau d'analyse des risques et pollutions industriels* (BARPI) summarized some of hydrogen's characteristics, including potential consequences in terms of accidents in transport-type applications.

These features are as follows:

- Given its small size, the hydrogen molecule is more likely to leak than any other gas. Hydrogen also embrittles metals, increasing the risk of tank rupture and the likelihood of leaks,

⁸³. Ammonia is produced by the reaction $N_2 + 3 H_2 \rightarrow 2 NH_3$. Ammonia liquefied at a temperature: -33°C may be stored in slightly refrigerated tanks at that temperature, making it easy to transport.

⁸⁴. This is the reverse reaction: $2 NH_3 \rightarrow N_2 + 3 H_2$.

⁸⁵. The *Suiso Frontier* is the world's first liquid hydrogen transport vessel. Built by Kawasaki Heavy Industries, this prototype was commissioned in 2019 to evaluate the technical problems associated with transporting hydrogen in liquid form, and once transported 55t of hydrogen between Australia and Japan in 2022. However, a faulty valve caused the gas to leak and ignite, but the fire did not spread. The vessel, which was docked in Port Hastings, Australia, was able to deliver its cargo to the port of Kobe, Japan.

⁸⁶. French Transport Regulatory Authority. The French rail transport market in 2022. December 2023 report. [Link](#).

⁸⁷. Rail transport currently consumes 10 TWh of electricity.

- In the presence of air, hydrogen easily ignites, in a process requiring very low ignition energies and that may occur over a wide range of compositions and ambient temperatures. A spark from an electrostatic discharge, for example, may suffice to ignite a mixture of hydrogen and air,
- Hydrogen flames are typically ten times faster than flames associated with hydrocarbon fuels,
- Hydrogen accumulated in a confined space can give rise to violent explosions and in some cases, if the conditions are right, this explosion can transition to a detonation⁸⁸.

Of course, other fuels, whether gaseous or liquid, also pose similar problems, which have long been successfully mastered thanks to appropriate regulations. But in the case of hydrogen, the difficulties are even greater:

- Hydrogen's flammability range, expressed in volume fractions, extends from 4 to 75%, an interval that is much wider than that of methane (5 to 15%), or propane (2.1 to 9.5%) or other gaseous alkanes.
- The minimum ignition energy for hydrogen/air mixtures is quite low (0.02 mJ versus 0.20 mJ

for gasoline vapors and 0.29 mJ for natural gas). At ambient pressure, the minimum auto-ignition temperature is around 520°C, which is slightly higher than that of gases such as methane (455°C), propane (450°C) and considerably higher than that of petrol (230°C) or diesel (210°C).

- The quenching thickness (the size of the mesh used to stop the progression of a flame in a duct) is significantly lower for hydrogen and air flames than for other combustible gases, making the propagation of hydrogen deflagrations more difficult to stop than that of hydrocarbon flames.

Hydrogen is more difficult to control than hydrocarbon fuels. The safety of hydrogen applications outside a strict industrial framework is more difficult to guarantee. For example, extension to the fields of transport or heating could become a critical issue and a source of limitation for the use of hydrogen if it were deployed on a massive scale. Figure 7 illustrates the two main hazard scenarios associated with hydrogen leaks, which may occur wherever this

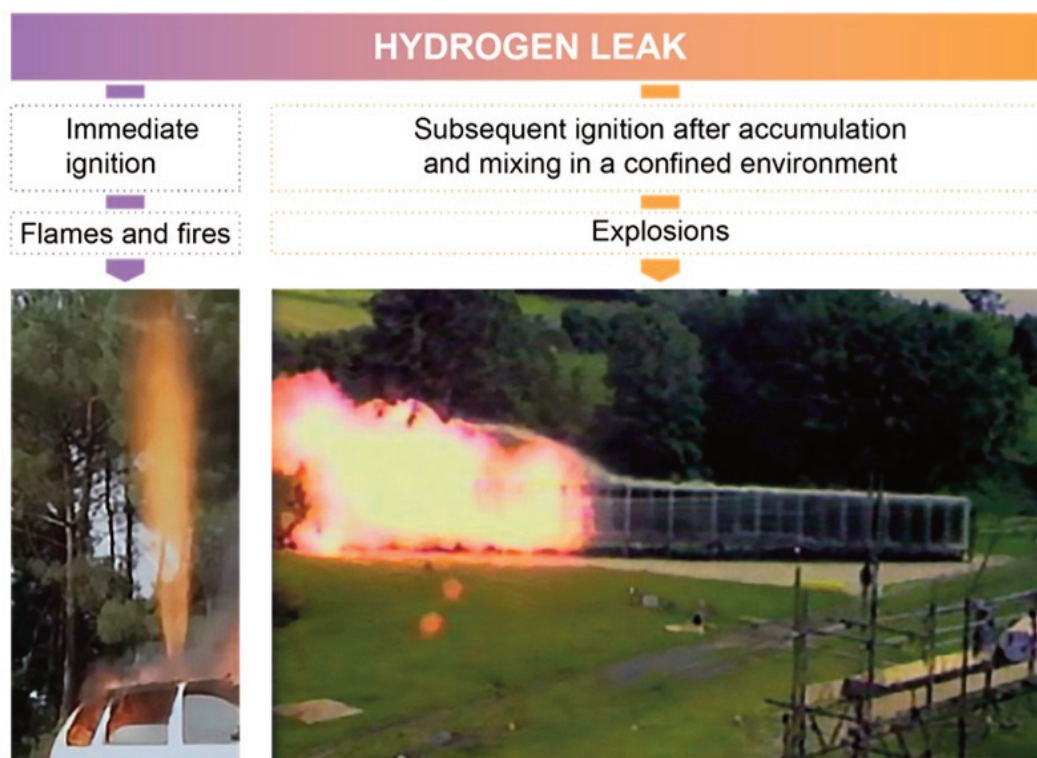


Figure 7⁸⁹. The two combustion safety scenarios for a gas leak. Left: hydrogen flame anchored to a high-pressure hydrogen tank. Right: explosion propagating in a rectangular channel.

⁸⁸. A detonation occurs when the flame front exceeds the speed of sound of the burnt gases, and the exothermic chemical conversion process is accompanied by a shock wave.

⁸⁹. www.dnv.com/spadeadam.

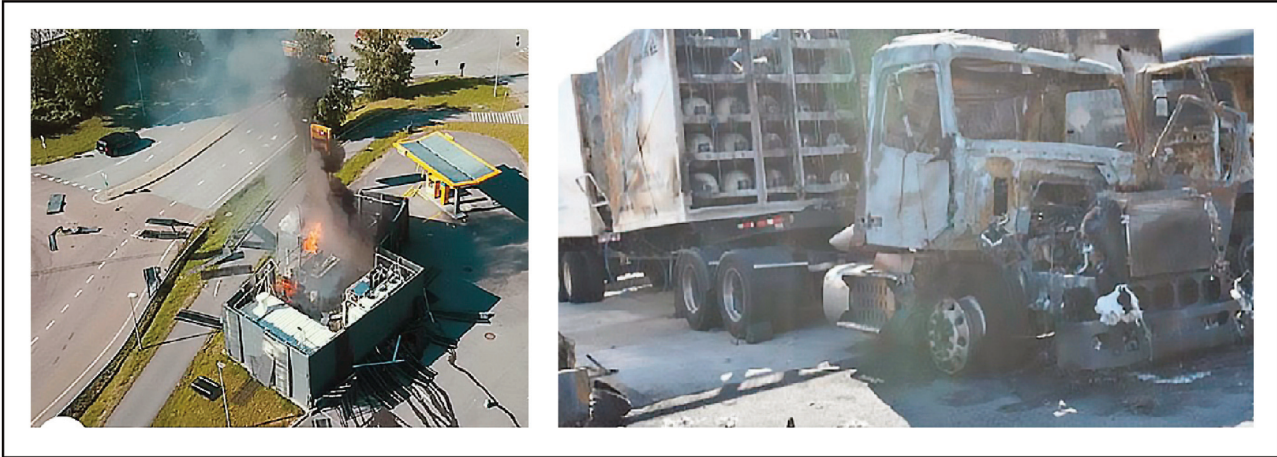


Figure 8⁹⁰. Examples of recent accidents related to hydrogen deployment. Left: filling station in Norway (June 10, 2019). Right: transport trucks in California at a hydrogen production site (June 1, 2019).

gas is stored, transported, or used, *i.e.* in tanks, pipes, valves, engines, fuel cells, etc. Leaks can lead to immediate ignition (Figure 7 left) and thus to a flame, which can be very long if the flow rate is large (several meters), very hot (combustion temperatures are higher than those of hydrocarbon flames), very powerful and virtually invisible, and quite difficult to detect.

The planned applications for hydrogen mean that it will be used in new, critical, and potentially dangerous conditions. For example, the use of high-pressure tanks (700 bar) in cars poses specific problems: at these pressures, there is a high probability that a hydrogen leak will lead to auto-ignition (in the absence of a spark), which is what probably happened at a service station in Norway in 2019 (Figure 8 left).

Fires are not the most worrying consequence of a hydrogen leak. The real danger comes from a hydrogen leak mixing for a long time with the air under confined conditions in a building, for example, before ignition takes place in a second stage (Figure 7 right). When an explosion is triggered under these conditions, it may give rise to a deflagration where the flame advances at a few m/s, burning everything in its path, accompanied by low pressure variations (1.01 to 1.05 bar) that do not destroy the structural walls of the building. However, these explosions can

also evolve into detonations, which propagate at higher speeds (more than 2 km/s) with significant pressure rises (100 to 150 bar), capable of destroying everything in their path. This is known as the deflagration-to-detonation transition (DDT). Hydrogen detonates easily, but it remains difficult to know whether a leak in each configuration will lead to detonation or not. This is one of the fundamental problems still unresolved by the combustion community.

Finally, one may also mention two other areas where safety will become a critical issue :

- (1) The use of liquid hydrogen at 20K envisaged, for example, for storage in aircraft gives rise to a number of issues. Their analysis and that of a "combustion" scenario induced by liquid hydrogen leakage remains patchy.
- (2) The combined use of hydrogen and oxygen, notably for decarbonized heat production in industry (cement, steel, glass, etc.). As only oxygen combustion can achieve the high temperatures required for certain processes, the transition to hydrogen/oxygen systems will become essential. Here again, even in an industrial setting, handling large quantities of these two gases will raise safety issues, which are well known in some specific fields like that of rocket propulsion (Ariane 5 and 6 use engines powered by

⁹⁰. <https://www.h2-mobile.fr/actus/incendie-station-hydrogene-norvege-que-sest-il-passe/>; https://h2tools.org/sites/default/files/2021-06/AP_Santa_Clara_Incident_Review_Report_Rev1.pdf.

cryogenic oxygen and hydrogen propellants), but whose transposition to other applications will not be trivial. For this reason, the industry will also need to deploy new electric furnaces capable of reaching the highest possible temperature values required for certain industrial processes.

The wider deployment of hydrogen in society should therefore be based on strict regulations, some of which have yet to be designed. For example, there are no regulations on hydrogen safety in aircraft or airports. Such regulations are impossible to define precisely today, as fundamental knowledge of the mechanisms controlling hydrogen fires or explosions is incomplete. Increased scientific knowledge in this field is essential if one wishes to define safe applications for hydrogen, while ensuring that the cost of safety protocols and systems remains compatible with these applications. The subject of "safe combustion" should be considered at an early stage for all hydrogen applications.

9. Decarbonized hydrogen: potential uses.

As already indicated (Figure 1), France currently consumes around 0.9 Mt of hydrogen, mainly

grey, mostly for industrial uses: refining of oil, ammonia synthesis (fertilizers) and the chemical industry (methanol synthesis, for example). All the 2050 scenarios extend, in varying proportions, these uses of hydrogen, now green⁹¹, to other sectors, notably transport, heating ("power-to-gas" for heat production) and inter-seasonal electricity flexibility ("gas-to-power") (Figure 9).

In this report, it was decided to leave aside the "power-to-gas" strategy, which involves using hydrogen to produce heat, particularly in the residential and commercial sectors, by injecting it into gas networks. Indeed, this use of hydrogen is not likely to be one of the priorities of tomorrow's hydrogen industry⁹², given, on the one hand, the loss of volumetric energy density and the cost of this fuel, and, on the other hand, the advantages of the electrification of heating, which is experiencing a favorable dynamic, with heat pumps for example.

It is however interesting to examine the use of hydrogen as a possible option for inter-seasonal energy storage and as a flexibility mechanism for balancing the supply of electricity. This involves "power-to-gas" and "gas-to-power" conversion strategies that may be used in principle

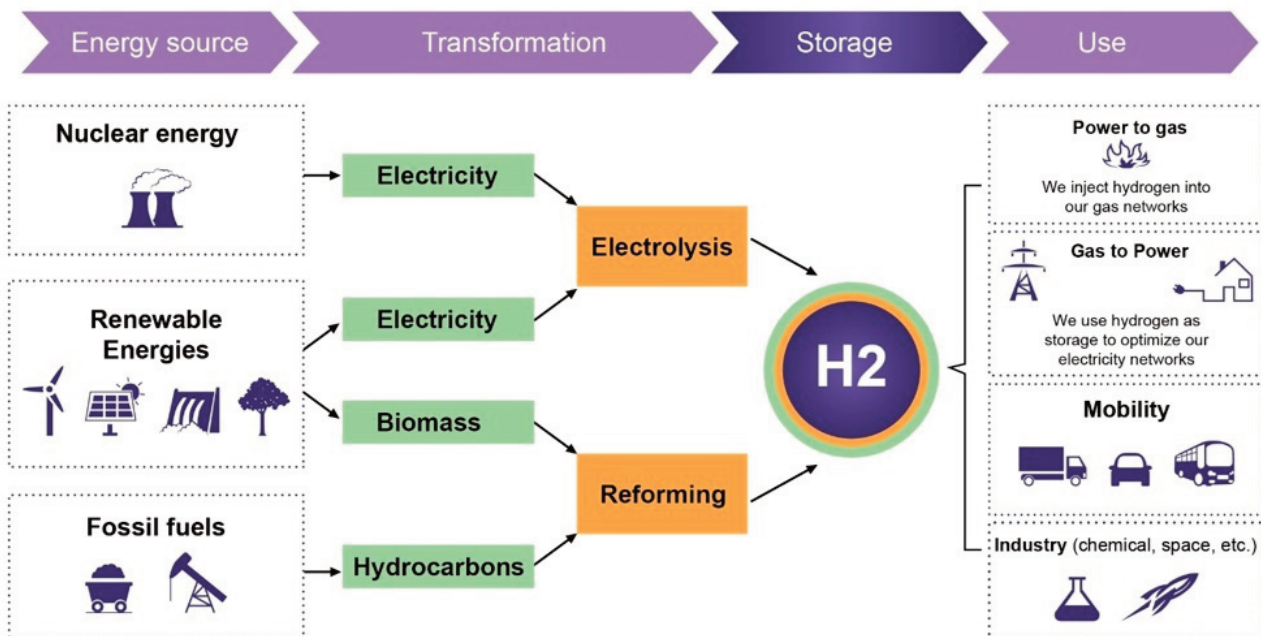


Figure 9. Medium-term outlook for the hydrogen sector.

⁹¹. The case of white, or natural, hydrogen is not considered here because, as we have shown above, everything remains to be discovered about the possibilities offered by this primary energy source.

⁹². French Academy of Technologies. The role of hydrogen in a low carbon economy. 2020. [Link](#).

to adapt supply to demand but are also problematic. Water electrolysis enables renewable electricity to be transformed into hydrogen, which can be stored for several months, during periods when it is produced in excess (particularly during the summer). This hydrogen can then be converted into electricity when there is a shortage of renewable electricity (particularly in winter), using hydrogen fuel cells⁹³ connected to the power grid⁹⁴. The amount of electricity to be stored in the form of hydrogen over a year obviously depends on a country's total electricity consumption and the share of intermittent energies. A recent study⁹⁵, in line with analyses by RTE⁹⁶, indicates that this quantity could rise to over 40 TWh in a French scenario consuming 750 TWh of electricity with 50% nuclear production. The major drawback of the whole "power-to-H₂-to-power" chain is its low energy efficiency, which is of the order of 25 to 30%⁹⁷(Figure 10), i.e. with an output of around 14 kWh for a 60 kWh input⁹⁸. Of the 40 TWh to be stored in the form of hydrogen, only around 10 TWh could be fed back into the grid, leaving a shortfall of 30 TWh. To make up the difference, one would have to be able to rely on additional controllable sources of electrical energy, or multiply intermittent

production capacities and the corresponding electrolysis capacities by a factor of around 3.5.

Nevertheless, these difficulties should not totally rule out the use, on a reasonable scale, of hydrogen to contribute to the flexibility of the power system, in the absence of other mechanisms for long-term inter-seasonal storage. The right balance will be ensured in part by the power system's limited dependence on intermittent sources, which are responsible for high storage requirements.

So, in the short term at least, the priorities for hydrogen use should be industry and mobility.

Hydrogen and industry.

Quite simply, the priority is to replace grey hydrogen with green hydrogen for current industrial uses. It is likely that some oil will still be used in 2050, particularly for non-electrifiable applications, for which alternative liquid fuels will not be available in sufficient amounts. Some hydrogen will therefore continue to be needed to refine this residual oil. Similarly, essential chemical compounds, such as methanol and

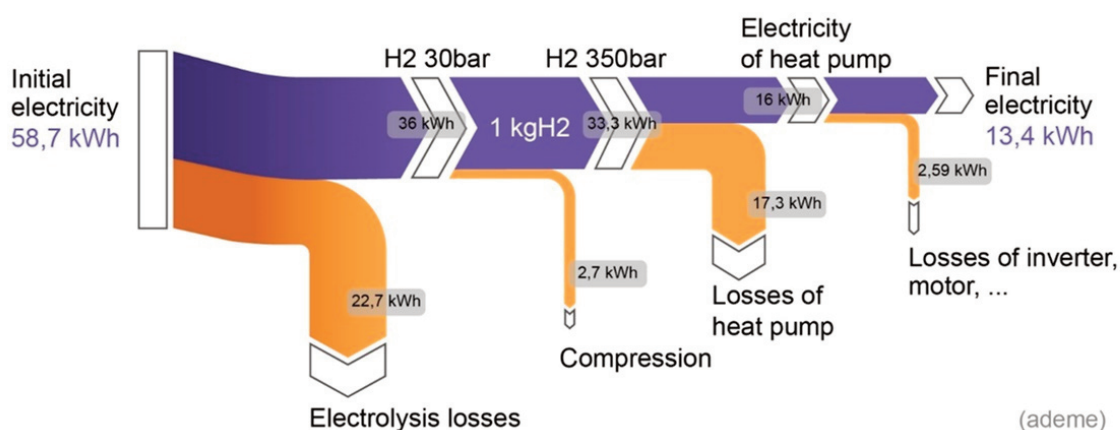


Figure 10⁹⁹. Energy losses along the power-to-hydrogen-to-power chain. Energies expressed in kWh correspond to the use of one kg of green hydrogen (from water electrolysis).

⁹³. Hydrogen fuel cells are electrochemical devices that work in the opposite way to electrolyzers, i.e. they carry out the reaction $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$ which produces electricity: at the anode, H₂ is oxidized to water and the electrons generated there are circulated through the electrical network to reach the cathode where O₂ is reduced to H₂O. Yields are limited (around 50%).

⁹⁴. A switch to methane by methanation reaction ($\text{CO}_2 + \text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$) is ruled out due to a significant degradation in energy yield. Fontecave M. and Grand D. Energy storage: the problematic efficiencies of the Power-to-Gas-to-Power sector. *Science et pseudo-sciences* n°340, April/June 2022. See [Link](#).

⁹⁵. Fontecave M. and Grand D. Energy scenarios put to the test of intermittent energy storage. *Comptes rendus - Chimie*. 2021, **24** : 331-50. [Link](#).

⁹⁶. RTE. Energy futures. 2021. [Link](#)

⁹⁷. A value estimated, for example, in an ADEME study, see: ADEME. Hydrogen chain efficiency - the case of "power-to-H₂-to-power". Fiche technique, January 2020. See [Link](#).

⁹⁸. With such efficiencies, converting hydrogen, produced by an electricity-consuming process, into electricity is highly questionable.

⁹⁹. ADEME. Hydrogen chain efficiency - the case of "power-to-H₂-to-power". Fact sheet, January 2020. [Link](#).

ammonia, will continue to be produced by the chemical industry, and thus require hydrogen. The corresponding hydrogen requirement can be estimated at 0.4 Mt.

The industry's second challenge is to hydrogenate processes that emit high levels of CO₂ and cannot be electrified, notably steel and cement production. In the first case, hydrogen¹⁰⁰ is used to replace coal¹⁰¹ in the reduction of natural iron oxide to metallic iron. Obviously, to reach the required industrial scale, and given the insufficient maturity of this new process, industrial developments are still necessary, and such work is being undertaken by steel companies such as Arcelor Mittal. The need can be estimated at 0.75 Mt of green hydrogen, based on a national steel production of 14 Mt¹⁰².

Cement production is also a major emitter of CO₂¹⁰³. The main contributors to these emissions are, on the one hand, the very high need for heat and, on the other hand, the very nature of the calcination reaction of cement limestone (CaCO₃ → CaO + CO₂), which extracts carbon from the ore in the form of CO₂¹⁰⁴. Many cement manufacturers (Vicat, Lafarge) are committed to decarbonizing their processes, notably by using green hydrogen. While this can be used to produce heat¹⁰⁵, it is more commonly envisaged to capture the CO₂ emitted by cement plants and combine it with hydrogen produced on-site by electrolyzers (e.g. Vicat and Hynamics' Hynovi project) to produce low carbon methanol

(CO₂ + 3 H₂ → CH₃OH + H₂O). Based on a level of emissions of 12 Mt of CO₂ in France associated with cement production, the corresponding hydrogen requirement can be estimated at 0,85 Mt.

Hydrogen and mobility.

The possibility of developing hydrogen-powered private cars is often evoked, as such vehicles (like hydrogen-powered buses) are already on the road, thanks to the development of hydrogen fuel cells and suitable hydrogen tanks.

However, the explosion of the battery-electric vehicle market, in France and worldwide, suggests that it has irreversibly won the competition with the hydrogen vehicle. The advantages of the latter lie in its range and the speed with which it can be refilled, which can't counterbalance the disadvantages, which are currently prohibitive: (i) Much higher purchase and running costs; (ii) Much lower energy efficiency than batteries (25% vs. 80%); (iii) Safety issues, such as the fires and explosions mentioned above.

A recent study by the Academy of Technologies¹⁰⁶ points out that "all reports indicate that the battery-powered light-duty vehicle will be deployed for a long time before the hydrogen-powered light-duty vehicle is". Finally, it should be noted that, in terms of carbon footprint over the entire life cycle, the hydrogen vehicle is significantly less favorable (Figure 11)¹⁰⁷. This transport mode will represent only a marginal

¹⁰⁰. The reaction is Fe₂O₃ + 3 H₂ → 2 Fe + 3 H₂O. It emits no CO₂ and over the whole chain of this new process, one can expect emissions of 0.1 kg of CO₂ per kg of steel produced.

¹⁰¹. The reaction is Fe₂O₃ + 3 CO → 2 Fe + 3 CO₂, using carbon monoxide (CO) from the mild oxidation of coal. This process is one of the highest CO₂ emitting industrial processes, i.e. 2 kg of CO₂ per kg of steel produced, so that the steel industry is responsible for 7 to 9% of global emissions

¹⁰². The French steel industry produces 14 Mt of steel, employs 30,000 people, and generates sales of 15 billion euros. It is a major exporter.

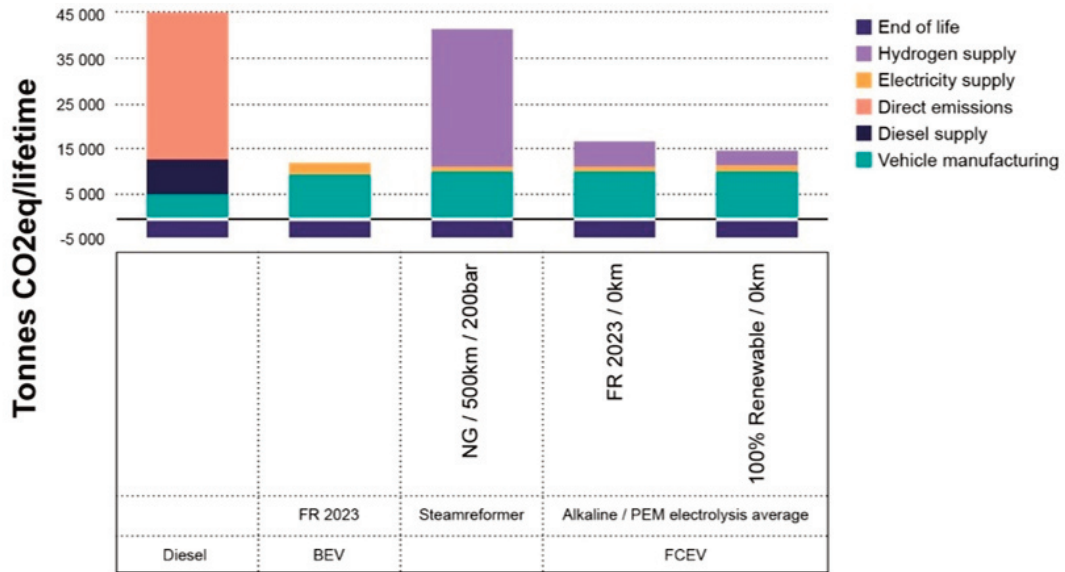
¹⁰³. Worldwide production of 4 Gt per year (including 18 Mt for France) is responsible for 6 to 8% of CO₂ emissions. These specific emissions are estimated at 1 t of CO₂ per ton of cement, broken down into 535 kg for limestone calcination, 330 kg for heat production and a further 141 kg for ore extraction and transportation. Davis J.S. *et al.*, Net-zero emissions energy systems. *Science*. **360**. 2018. DOI: [10.1126/science.aas9793](https://doi.org/10.1126/science.aas9793); Vasilakis, N. Life Cycle Assessment and Exergy Analysis of Concrete. 2001. Diploma Thesis, LHTEE/AUTH, Thessaloniki, Greece.

¹⁰⁴. Mixed limestone (80%) and clay (20%) are ground together, the powder calcined at 900°C and then heated to 1,450°C (in general using fossil fuels such as gas or coal) in a rotary kiln to form "clinker". After cooling, materials are added, the most important of which is slag, derived from the reduction of iron in blast furnaces used to produce steel. By calcinating the limestone, the carbon is removed from the limestone and the resulting lime recombining with the silica and alumina of the clay (SiO₂ -Al₂O₃) yields calcium silicate and aluminates, making up the cement.

¹⁰⁵. This is no simple matter, given the specific properties of hydrogen flames, and for the moment this is only possible by mixing hydrogen with carbon fuels (biofuels, biomass).

¹⁰⁶. French Academy of Technologies. The role of hydrogen in a low carbon economy. 2020. [Link](#).

¹⁰⁷. ADEME. Life cycle assessment of hydrogen. Hydrogen production and use in light mobility. September 2020. See [Link](#).



BEV (FR 2023) : Battery Electric Vehicle, or battery-powered electric vehicle of the French mix 2023.
 FCEV : Fuel Cell Electric Vehicle, or hydrogen electric vehicle.
 Steamreformer : steam reforming, with 100% natural gas.

Figure 11. Comparative CO₂ emissions for different vehicles.

part of mobility, mainly for semi-heavy vehicles (trucks, buses, vans, garbage collection vehicles)¹⁰⁸ or captive fleets (taxicabs in France relying on the Toyota Mirai hydrogen vehicle, for example).

Finally, one has to consider heavy transport, sea and air¹⁰⁹, which are also the most problematic. It's hard to imagine that these types of transport, and especially wide-body aircraft, will be able to run on electric means including batteries, electric motors, or hydrogen fuel cells by 2030, or even by 2050. In France, companies such as Airbus and Safran are making commendable efforts to develop hydrogen-powered aircraft. However, the advent of such aircraft must await major advances in the development of suitable propulsion systems, in the progress in the management of the extreme cryogenics required

for liquid hydrogen, in the lightening of storage tanks, in overall integration and, above all, in the safety of aircraft and airport infrastructures¹¹⁰.

It therefore seems that this type of transport will only continue to exist if liquid fuels are available, and these will probably include fossil fuels that are difficult to replace.

The "green" alternative is synthetic or alternative fuels, in other words, all biofuels and e-fuels¹¹¹, liquid and possibly gaseous fuels obtained by low carbon processes, i.e. excluding a fossil precursor, and using low carbon energy. For aviation, these are specifically sustainable aviation fuels (SAFs)¹¹². A synthetic fuel is therefore a hydrocarbon (gasoline, diesel, kerosene, oil) produced by a series of CO₂ transformation

¹⁰⁸. To illustrate what a complete switchover of freight and public transport to hydrogen fuel cells would represent, it is informative to consider the current figures (French ministry of ecological transition and territorial cohesion. *Les chiffres clés des transports-Edition 2022*. [Link](#)): the former consumes 17 Mtoe and the latter 3 Mtoe, corresponding to 250 TWh out of a total of 520 TWh, the remainder being consumed by private cars. Considering the yields of the Power-to-H₂-to-Power chain, this would require 250 TWh of hydrogen, i.e. 250/33 = 7.5 Mt of hydrogen, an extraordinarily large figure! And to produce them, would need around 400 TWh of electricity (i.e. (250×55)/33), a value greater than current nuclear production!

¹⁰⁹. Air transport currently consumes around 50 TWh of liquid fuel (around 5 Mt and 8 Mt in 2050), and shipping requires 25 TWh.

¹¹⁰. Hydrogen-powered aircraft will have unavoidable limitations due to the properties of this fuel, particularly in terms of passenger numbers and distances that can be covered (with H₂ liquid, less than 1,500 km, and with H₂ pressurized gas, less than 500 km). This is due both to the low volumetric energy densities and the heavy weight of the tanks, which leads to very low indices (mass of fuel/mass of full tank with accessories) (5% for H₂ gas at high pressure - 700 bar and 16 to 20% for liquid H₂, compared with kerosene).

¹¹¹. The prefix e- means that the synthesis process depends on an electrical resource, for example the hydrogenation of CO₂ by hydrogen obtained from the electrolysis of water.

¹¹². SAF stands for Sustainable Aviation Fuel.

reactions involving hydrogenation (notably by means of synthesis gas, a mixture of CO and H₂, and Fischer-Tropsch type catalytic reactions¹¹³). Production therefore depends on the availability of massive quantities of green hydrogen and CO₂, recovered, for example, from the most emitting industrial centers.

For shipping, which today requires 25 TWh of fuel, it is interesting to make a simple calculation: assuming that ships are powered by methanol (and the same energy level were to be obtained with another fuel) and considering that the yield of hydrogenation of CO₂ into methanol is 100%, this would need 5.5 Mt of CO₂ and 0.75 Mt of hydrogen¹¹⁴.

The same reasoning can be applied to air transport. In France, by 2050, forecasts for this sector point to a total demand for 8 Mt of fuel, of which, according to European Commission recommendations, 6 Mt should be sustainable aviation fuels (SAF), divided into 4 Mt derived from biofuels¹¹⁵ (excluding first-generation

biofuels, which are the only ones currently available) and 2 Mt of synthetic kerosene. Producing these 2 Mt of kerosene would require around 1.4 Mt of hydrogen.

This broad assessment shows that, while hydrogen consumption for current industrial uses is naturally declining (from 0.9 to 0.4 Mt), new uses for hydrogen in the production of "green" steel and cement call for an additional demand of 1.6 Mt. If one adds the demand for synthetic liquid fuels for the heaviest forms of transport (sea and air), the requirement by 2050 is just over 4 Mt¹¹⁶, the upper limit of all the scenarios, and this without considering the hydrogen that might be needed to ensure inter-seasonal flexibility (0.5 Mt). The production of 4 Mt of hydrogen would correspond to a requirement of around 230 TWh of electricity production dedicated to the production of green hydrogen. Such a scenario is not very realistic, and it is unlikely that one will be able to exceed 2 Mt. The industry will have to make choices about the future uses of the hydrogen it produces.

¹¹³. The typical reaction being of the form $(2n+1) H_2 + n CO \rightarrow C_n H_{2n+2} + n H_2O$.

¹¹⁴. The yield is closer to 80% (Fang X, Men Y, Wu F *et al.* Improved methanol yield and selectivity from CO₂ hydrogenation using a novel Cu-ZnO-ZrO₂ catalyst supported on Mg-Al layered double hydroxide (LDH). *Journal of CO₂ Utilization*. 2019, **29**: 57-64. <https://doi.org/10.1016/j.jcou.2018.11.006>), making a requirement of 1 Mt of hydrogen instead.

¹¹⁵. In a recent report, the French Academy of Technologies criticizes this breakdown, stating that biofuels will not be able to provide more than 20% of aviation fuels: French Academy of Technologies. *La décarbonation du secteur aérien par la production de carburants durables*. 2023. [Link](#). This conclusion is supported by another study: Transport et Environnement. How to decarbonize aviation in Europe by 2050? March 2022. [Link](#).

¹¹⁶. The French Academy of Technologies published a note on January 31, 2024, giving a range for decarbonized hydrogen requirements of 3.9 to 5.6 Mt, with the high estimate making certain assumptions that the note itself describes as not very credible. It points out that the targets for the installation of electrolyzer capacity in 2030-2035 and to produce decarbonized hydrogen are excessive in relation to anticipated hydrogen demand over this timeframe (French Academy of Technologies. *Y aura-t-il trop d'électrolyseurs en 2035 en France pour la demande prévisible ?* 2024. [Link](#)).

Conclusions et recommendations

Given the current state of knowledge, the prospects offered by natural hydrogen remain highly uncertain. Nevertheless, it is reasonable to recommend:

- **Rapidly and unhesitatingly support exploration projects on French soil** aimed at rigorously assessing the real potential for natural hydrogen.

For the time being, the development of decarbonized hydrogen is essentially based on **green hydrogen**, which needs to be promoted at least to

- **Decarbonize current uses**, replacing grey hydrogen, whether in refining (there will still be oil to refine in 2040-2050), ammonia production (fertilizers) or petrochemicals (syngas, methanol). This represents 0.9 Mt of hydrogen today, perhaps 0.4 Mt in 2050 (assuming less refining).
- **Decarbonize new uses**, particularly in sectors where direct electrification will not be possible in the short term, such as steel (replacing the coke process with a hydrogen process) and cement production, or for heavy mobility with the production of advanced fuels (or alternative fuels), from CO₂ by hydrogenation, at a level that remains difficult to anticipate today, but which could correspond to an additional 1 Mt

However, the conditions for this development are still far from being in place. If we are to create a positive dynamic in this direction, it is already possible to define some broad guidelines. These include:

- **Rapidly increase additional electricity production capacities.** Each million tons of green hydrogen (produced by electrolysis) requires around 55 TWh of electricity, equivalent to 5 x 1600 MW EPR reactors. The level of hydrogen production and consumption must remain compatible with the trajectories of the electricity mix defined within the framework of energy planning (Multiannual Energy Program - PPE, SNBC).
- **Rapidly increase electrolysis capacity while improving different technologies**, particularly those that are less mature, such as high-temperature electrolysis. This will reduce the

production cost of green hydrogen, a prerequisite if hydrogen is to play a significant role in the energy system of the future. Today, the price is between 4 and 8 euros/kg H₂ depending on the technology (1.5-2 euros/kg H₂ for grey hydrogen) and the aim is to lower this price to less than 3 euros/kg H₂.

- **Rigorously assess the carbon footprint of new hydrogen processes** and uses across all value chains.
- **Strictly control the level of hydrogen imports**, to avoid moving from one high level of external dependence (fossil fuel imports) to another (hydrogen imports).
- **Undertake a massive effort on safety issues**, particularly in the transport sector. Accidents caused by hydrogen could block its deployment. Safety, for example, has become the main issue for hydrogen-powered aircraft.
- **Implement a strict policy of arbitration, by defining priorities between the different uses of hydrogen.** Given that it will not be possible to hydrogenate everything, priority must be given to using green hydrogen to decarbonize industry and certain forms of transport, ahead of other uses such as the "power to gas" (for residential and commercial heating) and "gas to power" (for example, to power hydrogen-powered cars, which are less energy-efficient than electric cars, or to ensure the flexibility of the electricity system).
- **Pursue strong fundamental and technological research** to improve the energy efficiency of electrolyzers and hydrogen fuel cells and reduce their environmental footprint (need for non-noble metals), to improve the stability and reduce the weight of tanks through the development of new materials, to improve the capacities of materials and molecules for storing and transporting hydrogen, and to make more efficient use of ammonia as a hydrogen carrier.

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Authors

Marc FONTECAVE

Collège de France, member of the French Academy of Sciences.

Sébastien CANDEL

CentraleSupélec, member of the French Academy of Sciences.

Thierry POINSOT

CNRS, member of the French Academy of Sciences.

EDITORIAL SECRETARIAT

Juliette ROCHET

Director of committees, opinions and reports of the French Academy of Sciences.

Florent GOZO

Assistant to the Director of Committees, Opinions and Reports at the French Academy of Sciences.

Illustrations

Oksana PISHKO

MEMBERS OF THE PROSPECTIVE ENERGY COMMITTEE (CPE) OF THE FRENCH ACADEMY OF SCIENCES

Roger BALIAN

Sébastien BALIBAR

Lydéric BOCQUET

Yves BRÉCHET

Catherine BRÉCHIGNAC

Édouard BRÉZIN

Sébastien CANDEL

Catherine CESARSKY

Bruno CHAUDRET

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Michel POUCHARD

Daniel ROUAN

Didier ROUX

Christian SERRE

Patrice SIMON

Jean-Marie TARASCON

Jean WEISSENBACH

Francis-André WOLLMAN

EXPERTS INTERVIEWED FOR THE STUDY

Christophe PROUST

DR Ineris and Professor at Compiègne University of Technology.
Auditioned on 10/19/21.

Franz LAHAIE

Hydrogen project manager at Ineris.
Auditioned on 10/19/21.

Florence LAMBERT

President of GENVIA, member of the French Academy of Technologies.
Auditioned on 11/23/21.

Matthieu THOMAS

Head of the H₂ aircraft program at Airbus.
Auditioned on 01/02/22.

Isabelle MORETTI

Associate researcher at E2S - Université de Pau et des pays de l'Adour (UPPA), member of the French Academy of Technologies and expert on natural H₂ deposits.
Auditioned on 01/15/24.

Michel WACHENHEIM

President of the French Air and Space Academy (AAE).
Auditioned on 02/05/24.

Xavier BOUIS

Chairman of the Energy and Environment Commission of the French Air and Space Academy (AAE).
Auditioned on 02/05/24.

Jacques PIRONON

DR CNRS, GeoRessources Laboratory - UMR CNRS/University of Lorraine.
Auditioned on 03/07/24.

Philippe de DONATO

DR CNRS, GeoRessources Laboratory - UMR CNRS/University of Lorraine.
Auditioned on 03/07/24.

ABBREVIATIONS, ACRONYMS, FORMULAS AND SYMBOLS USED

Abbreviations and acronyms

ADEME	French Environment and Energy Management Agency
BARPI	Industrial Risks and Pollution Analysis Office
CNRS	French National Center for Scientific Research
DDT	Deflagration to detonation transition
DOE	U.S. Department of Energy
EDF	<i>Électricité de France</i>
EPR	European/evolutionary Power Reactor
eqCO ₂	CO ₂ equivalent of a greenhouse gas emission
ERDF	European Regional Development Fund
EU	European Union
GHG	Greenhouse gases
IEA	International Energy Agency
LCA	Life cycle assessment
LOHC	Liquid Organic Hydrogen Carrier
MOFs	Metal Organic Frameworks
NZE	Net Zero Emissions
OPECST	Parliamentary Office for the Evaluation of Scientific and Technological Options
PEM	Proton Exchange Membrane
PPE	Multiannual energy plans
R&D	Research & Development
RTE	<i>Réseau de transport d'électricité</i>
SAF	Sustainable Aviation Fuels
SNBC	Government's National Low Carbon Strategy, first adopted in 2015

Chemical symbols and formulas

CH ₃ OH	Chemical formula of the methanol molecule
CH ₄	Chemical formula of the methane molecule
CO	Chemical formula of the carbon monoxide molecule
CO ₂	Chemical formula of the carbon dioxide molecule
H ₂	Chemical formula of the dihydrogen molecule, often referred as hydrogen
H ₂ O	Chemical formula of the water molecule
H ₂ S	Chemical formula of the hydrogen sulfide molecule
MgH ₂	Chemical formula of the magnesium hydride molecule
NaBH ₂	Chemical formula of the sodium tetrahydruoborate molecule
NH ₃	Chemical formula of the ammonia molecule
NH ₃ BH ₃	Chemical formula of the ammonoborane molecule, also known as borazane
N ₂ O	Chemical formula of the dinitrogen monoxide molecule
CaCO ₃	Chemical formula of the calcium carbonate molecule
CaO	Chemical formula of the calcium oxide molecule
Co	Symbol for cobalt (chemical element)
Fe	Symbol for iron (chemical element)
Ni	Symbol for nickel (chemical element)

°C	Symbol for degree Celsius (temperature unit)
J	Symbol for joule (unit of energy); $1\text{mJ}=10^{-3}\text{J}$
K	Symbol for degree Kelvin (temperature unit)
g	Symbol for gram (unit of mass); $1\text{kg} = 10^3 \text{g}$
km ²	Symbol for square kilometer (unit of area)
L	Symbol for liter (unit of volume)
t	Symbol for ton (unit of mass); $1\text{Mt} = 10^6 \text{t}$ et $1\text{Gt} = 10^9 \text{t}$
toe	Symbol for ton of oil equivalent (unit of energy); $1 \text{ toe} = 42 \text{ GJ}$
W	Symbol for Watt (unit of power); $1\text{MW} = 10^6 \text{W}$ et $1\text{GW} = 10^9 \text{W}$
Wh	Symbol for watt-hour (unit of energy); $1\text{kWh} = 10^3 \text{Wh}$, $1\text{MWh} = 10^6 \text{Wh}$, $1\text{GWh} = 10^9 \text{Wh}$, $1\text{TWh} = 10^{12} \text{Wh}$

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23, quai de Conti - 75006 Paris
academie-sciences.fr