carbone4

# LOW-CARBON HYDROGEN: WHAT ARE THE RELEVANT MEDIUM-TERM USES IN A DECARBONIZED WORLD?

October 2022

Study conducted by Zeina Chaar, Consultant, Baptiste Rouault, Consultant and Aurélien Schuller, Manager.

Proofreading and contact:
Alexandre Joly, Head of the Energy Division
alexandre.joly@carbone4.com

This study was partly financed by mirova
Investing in sustainability

# Table of contents


Summary of the study ....4

I - Introduction .... 8

II - Hydrogen currently ....10

What is hydrogen? ....10

What is hydrogen used for today? ....11

Hydrogen is today mainly produced from fossil sources, so it has a high carbon footprint .... 12

Electrolysis allows the production of low-carbon hydrogen, if the electricity is itself low-carbon .... 16

Current and future costs for low-carbon hydrogen .... 17

III - What are the prospects for hydrogen consumption? ....19

Presentation of the general modelling framework .... 19

What are the prospects for hydrogen in the industry? ....22

- Ammonia and methanol production .... 22
- Steel industry .... 24
- Industrial heat .... 26

What are the prospects for hydrogen in transport? ....27

- Maritime ....27
- Aviation .... 31
- Trucks .... 34
- Railway ....39

What are the prospects for hydrogen in the energy sector? .... 40

- Refining .... 40
- Mixed consumption in gas networks .... 41
- Storage for the electric power system .... 43

Overview and conclusions.... 47

Relevance analyses within the studied uses .... 47

Analyses of relevance between the uses studied .... 49

Conclusions .... 51

# Summary of the study

## Context: low-carbon hydrogen raises hopes to respond to the climate emergency

**Respecting the Paris Agreement means "avoiding the unmanageable"** by limiting the worsening of the climate change that is already underway. To do this, we need a strong and quick reduction of global greenhouse gas emissions, that must come with **a sharp decrease in the consumption of fossil fuels**. To achieve this, a small molecule is giving rise to a lot of hope: **hydrogen. If not carbon intensive, it is an answer to dealing without fossil fuels for certain activities** and managing the energy transition, while strengthening our independence.

In this context, **Carbone 4 has conducted a prospective study on the potential of low-carbon hydrogen according to the different consumption segments** and considering other decarbonizing options, in order to **enlighten the public debate on the most efficient uses of hydrogen** to respond to the climate emergency.

## Hydrogen today: mainly consumed in industry, it is mainly produced from fossil sources

**Most of the hydrogen is currently used as a feedstock in the industrial sector**. Worldwide, it is currently consumed at about 115 $MtH_2$ per year, with a slight increase in recent years. 70% of the consumption is distributed among refining, and methanol and ammonia production.

**On the one hand, hydrogen is largely** (approx. 40%) **a co-product of activity** (e.g. in coke oven gases). **On the other hand, the "dedicated production"** (approx. 60%), **hydrogen is today almost entirely produced from fossil resources**: coal gasification and especially steam reforming of natural gas represented more than 99% of dedicated hydrogen production in 2018. **Hydrogen thus currently has a high average carbon footprint**[1]: 15 $kgCO_2e$ / $kgH_2$ for dedicated hydrogen production, making it **one** of the **energy carriers with the highest carbon footprint**.

## Decarbonizing hydrogen production is possible through electrolysis, but will potentially remain more expensive than fossil production

However, there are **processes allowing the production of a less carbon intensive hydrogen, even though these processes are usually more expensive. The main one, electrolysis,** consists of

[1] We reason in terms of carbon footprint: the impact on the climate of hydrogen production does not only depend on the direct emissions of the production processes, but also on the upstream emissions to produce the electricity or the molecule from which hydrogen is derived. In the case of methane steam reforming, for example, the upstream emissions of the gas chain are very significant, leading to a carbon footprint of 13 $kgCO_2e$ per kg of hydrogen, while the direct emissions are of the order of 10 $kgCO_2e$ per kg (a figure found in many other studies about hydrogen).

separating the dihydrogen molecule from the oxygen atom that makes up the water molecule, with a high electricity consumption.

**Electrolysis enables the production of low-carbon hydrogen if the electricity itself is low-carbon**. Thus, electricity with a **carbon content lower than 60 $gCO_2e$ / kWh is** required **to produce low-carbon hydrogen** as we define it in this study. We have retained the carbon footprint threshold according to the European Taxonomy, **i.e. 3 $kgCO_2e$ / $kgH_2$**.

**In terms of cost, based on energy prices before the Ukraine war, low-carbon hydrogen by electrolysis would not be competitive with hydrogen from fossil sources**. According to our prospective modelling, the cost of production by electrolysis could be between 3 and 4 € per kg of hydrogen by 2030, compared to about 1 € for production from fossil sources. These analyses are nevertheless very sensitive to the hypotheses concerning the price of the different energies. As a matter of fact, the production cost of fossil hydrogen from natural gas, whose price has recently exceeded €100/MWh, would oscillate around €5 per kg of hydrogen. It is the same dynamic with the current market prices of electricity for electrolysis.

## Study approach: evaluate the potential of low-carbon hydrogen by 2030 for 11 uses, especially through a cross-analysis between these uses

We considered a set of 11 possible uses of hydrogen, distributed within 3 sectors, with a **temporal focus on low-carbon hydrogen consumption by 2030**.

| Industry | Transportation | Energy |
|---|---|---|
| Ammonia production | Sea | Mixed consumption in gas networks |
| Methanol production | Air | Storage for the electrical system |
| Steel production | Road: trucks | Refining |
| Heat use | Railway | |

The study of a potential low-carbon hydrogen use starts by **assessing its relevance within the use, based on its unitary decarbonization potential** [2] **and its comparative advantages or disadvantages compared to other decarbonizating options**. Then, we have determined **potential volumes of low-carbon hydrogen for the different uses**, notably, when possible, using sector decarbonization targets to deduct these volumes in a normative way.

The great interest of the study lies in the last step, which is to proceed to an **inter-use or inter-sector analysis, in order to result in an order of merit for the use of low-carbon hydrogen among the different uses studied**. This analysis is based on the **decarbonizing intensity of hydrogen**: this metric, expressed in $tCO_2e$ / $tH_2$, translates **the reduction of the carbon footprint (expressed in $tCO_2e$) of a use that low-carbon hydrogen enables, for one unit of hydrogen (expressed in $tH_2$)**.

[2] The unitary decarbonization potential is the proportion of carbon footprint reduction that low-carbon hydrogen allows within a given use. It is said to be "unitary" in the sense that the decarbonization is related to a volume of activity of the underlying studied: for example, decarbonization per ton of steel for the steel industry, or decarbonization per km driven for trucks.

## Lessons learned from the study: low-carbon hydrogen should be prioritized for ammonia and methanol production, direct reduced iron for steel production and e-LNG and e-methanol for the maritime sector

For the current uses of hydrogen, which are the **production of ammonia**, mainly for manufacturing fertilizers, **and the production of methanol**, it is **necessary and a priority to substitute fossil hydrogen with low-carbon hydrogen** in order to decarbonize these uses for which few other solutions exist.

**The steel industry (for the direct reduction of iron ore) and the maritime sector (for the production of e-LNG and e-methanol) will necessarily need low-carbon hydrogen in the medium term to follow their 2°C trajectory**. For both sectors, hydrogen is essential and complementary to other solutions: the development of recycling and carbon capture for steel, and bioenergy for maritime. For marine fuels, e-LNG can be easily used in existing or new LNG ships to reduce greenhouse gas emissions and save natural gas.

**The use of hydrogen as a flexibility brick for electrical systems will probably be unavoidable**, in the medium term and especially in the long term, to accompany the development of variable electricity production means, such as wind power and photovoltaic pannels.

**The aviation sector will also need access to low-carbon hydrogen for synthetic fuels**, again as a complement to bioenergy, **but in the longer term**: the potential volumes in 2030 are almost zero. Hydrogen for direct use in aviation will not see the light of day before 2035 because the technologies are not mature enough.

**For refineries, the relevance of low-carbon hydrogen is uncertain**: they could benefit from the use of low-carbon hydrogen now, even if the decrease in emissions is proportionally low. It is likely that carbon capture is a pathway that better fits the sector's needs, even if its decarbonization cannot be entirely based on this solution (limited accessibility to deep geological storage). Finally, an allocation of hydrogen in this sector must be made taking into account the necessary decrease in the volumes of activity in the sector over the coming decades.

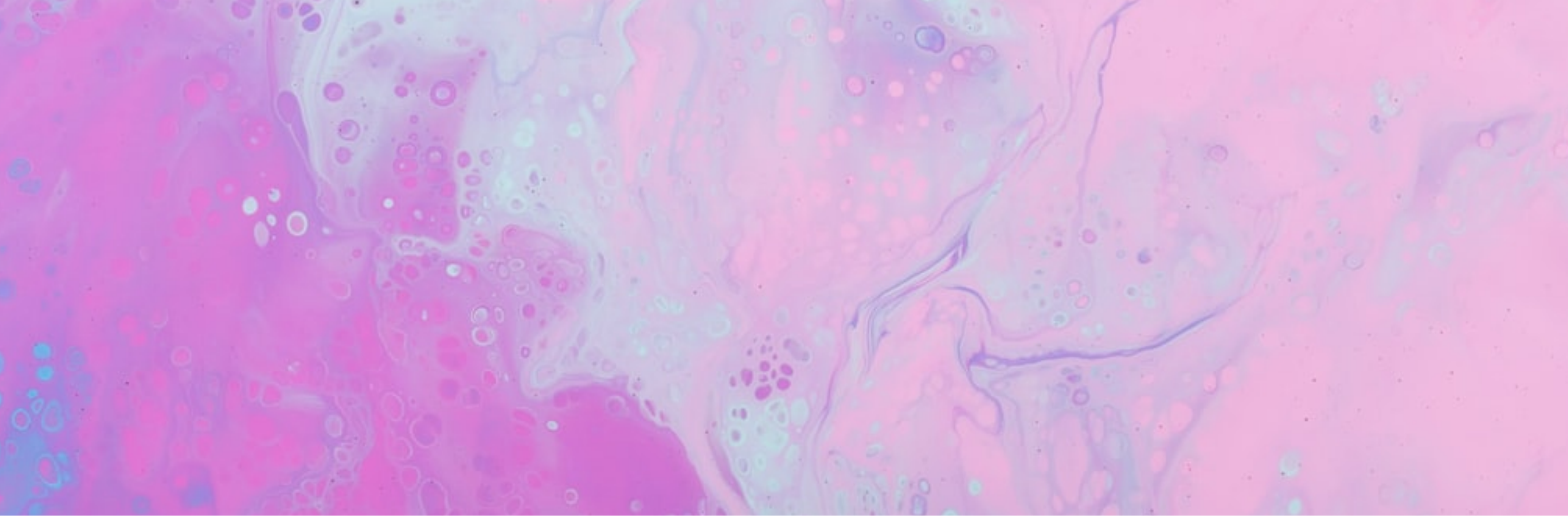
**For railways and trucks, the use of hydrogen is relevant but in limited quantities for certain very specific situations** (strong need for autonomy for example, or in the form of hybridization between batteries and hydrogen within the same vehicle). These sectors will be decarbonized through electrification. Although the unitary decarbonization potential of hydrogen is high in these sectors, the decarbonization intensity[3] of hydrogen is low. It is therefore preferable to use low-carbon hydrogen for other uses.

**For the production of ammonia as a synthetic fuel for the maritime sector, the allocation of low-carbon hydrogen is not relevant**: there are still uncertainties about the technology on the one hand (incomplete combustion leading to nitrous oxide emissions and toxic ammonia leaks) and above all, as the decarbonizing intensity is lower than for other fuels, it is preferable to use low-carbon

[3] This metric, expressed in $tCO_2e$ / $tH_2$ , translates the reduction of the carbon footprint (expressed in $tCO_2$ e) of a use made possible by low-carbon hydrogen, compared to a unit of hydrogen (expressed in $tH_2$ ). It allows to compare the different uses between them, in the perspective of a constrained allocation of a limited volume of low-carbon hydrogen available at the considered time horizon. In order to get the highest possible decarbonization through low-carbon hydrogen, it will be necessary to allocate it to the uses that present the best emission reduction per ton of hydrogen.

hydrogen for other uses, whether for the production of the other synthetic fuels studied within the maritime sector, or else for other sectors.

**Hydrogen consumption in gas networks and hydrogen injection in blast furnaces are not relevant applications to be developed for hydrogen**, because they do not generate enough emission reductions in their sectors. The decarbonizing intensity of these uses is also low, in absolute terms for hydrogen consumption in gas networks, or compared to the direct reduction of iron ore in the case of the steel industry.



# I - Introduction

*The climate emergency*

In December 2015 at COP21, the international community made a commitment to **limit global warming under 2°C or even 1.5°C**. This is known as the "**Paris Agreement**". This level of warming corresponds, according to the state of scientific knowledge, to the **threshold that must be respected in order not to lead our climate system irreversibly into an uncontrolled dynamic of warming**, due to the positive feedback loops[4].

**Climate change is already here**, as we are regularly and sadly reminded by numerous news. However, the consequences that are unfolding before our eyes are only the effect of past greenhouse gas emissions. Current and future emissions will, in any case, contribute to **an on-board climate disruption to which we will have to adapt**, in order to **"manage the inevitable"**. What the Paris Agreement is about is **limiting the worsening of the climate change already on board, and thus "avoiding the unmanageable".**

To meet the Paris Agreement, a **strong and rapid reduction in global greenhouse gas emissions** is needed. $CO_2$ emissions from energy combustion alone account for two-thirds of greenhouse gas emissions[5]. Without concealing the importance of reducing the emissions of the other third of greenhouse gas emissions[6], we must **rapidly and resolutely commit to a sharp decrease in the consumption of fossil fuels**: the consumption of coal, oil and gas must decrease by 4 to 7% each year. **Reinventing our energy system**, which is **currently 80% dependent on fossil fuels, will thus be necessary**. At the same time, this trend must be combined with **the acceleration of the development of low-carbon energies and the evolution towards business models that include the sufficiency of energy use**.

[4] Examples: thawing of permafrost, forest fires, reduction of albedo by melting ice (the surface of the ice is more reflective than the open water or land that its melting uncovers).
[5] Expressed as 100-year global warming potential.
[6] Emissions from land use change (including deforestation), agriculture and some industrial processes.

*The momentum around hydrogen*

In this context, **a small molecule is raising a lot of hope: hydrogen**.

**Low-carbon hydrogen** is a **response to** the need to do **without fossil fuels for certain uses** and to **achieve the energy transition**. This energy carrier has been attracting more and more attention in recent years and is the subject of **commitments from public authorities**, particularly in the context of **the recovery plans** announced following the coronavirus crisis, for example at the European Union level in the "Next Generation EU" plan or at the French level in the "France Relance" plan.

*Issues addressed in this study*

In this context, Carbone 4 has conducted a **prospective study on the potential of decarbonized hydrogen according to the different consumption segments and taking into account other decarbonizing options**, in order to **inform the public debate on the most efficient uses of hydrogen to respond to the climate emergency.**

# II - Hydrogen currently

## What is hydrogen?

*Reminders and some physico-chemical properties*

**Hydrogen is the simplest chemical element, in the** sense that it is composed of only one proton. However, in everyday language, the word "hydrogen" is used by abuse of language, and this report will be no exception, to **refer to dihydrogen ($H_2$)**, a gas composed of two hydrogen atoms. It is the smallest molecule in existence. Dihydrogen (called hydrogen or $H_2$ in the following) is present in gaseous form at the usual conditions of pressure and temperature but can also liquefy by lowering its temperature to -253°C.

**Hydrogen allows the storage of energy in chemical form and its restitution in the form of electricity via a fuel cell or in the form of heat via its combustion, which has the particularity of not directly emitting $CO_2$**[7]. It also has a high gravimetric energy density (3 times more than diesel) but a low volumetric energy density at room temperature (hydrogen liquefied at 250°C has a volumetric energy density -4 times lower than diesel at room temperature), characteristics that can be a constraint in certain situations, for example in its use as on-board fuel for the mobility sector.

**Comparison of the main physico-chemical characteristics of dihydrogen and diesel**

| Main physico-chemical characteristics | $H_2$ | Diesel | Unit |
|---|---|---|---|
| Density at room temperature | 0 | 750 | kg/m³ |
| Mass energy density | 34 | 13 | kWh/kg (PCI) |
| Energy density by volume at standard temperature | 3 | 9 750 | kWh/m³ |
| Density by volume at -250°C | 71 | / | kg/m³ |
| Energy density by volume at -250°C | 2 385 | / | kWh/m³ |

*Is hydrogen a greenhouse gas?*

At the end of 2021, a study by the Environmental Defense Fund[8] relayed by the media outlet Euractiv, warned of the **indirect warming potential of hydrogen released into the atmosphere, which could "*prolong the lifespan of methane in the atmosphere*"**. The potential climate risk has also been confirmed by other scientists to Euractiv. This warming effect comes from the possibility that hydrogen reacts sufficiently with the hydroxyl radical (OH) to decrease its global average concentration over a significant period. The OH radical is the main atmospheric "detergent" that gets rid of pollutants, methane and other volatile organic compounds in the atmosphere. Changing its concentration thus has an impact on the lifetime of the species it removes.

[7] Dihydrogen does not contain a carbon molecule, and only emits water upon combustion. The chemical equation for the reaction is: $2\ H_{2\,(g)} + O_{2\,(g)}$à $2\ H_2O_{\,(l)}$.

[8] Non-governmental organization working in the field of environmental protection in the United States.

Recently, a BEIS study[9] estimated the warming power of hydrogen in the atmosphere to be eleven times (±5) that of carbon dioxide over 100 years. Currently, the only study evaluating the warming power of hydrogen evaluated it at about 6 times that of $CO_2$ over 100 years and it is this value that was taken up by the IPCC in its 2007 report. **However, this effect is still subject to uncertainties in the scientific community** and the extent of the issue should be the subject of further research, for example in the framework of the CICERO project in Norway, in which the CEA is participating, and whose conclusions are expected in 2022.

**If this indirect warming effect were to be confirmed, it could have a significant impact on the carbon footprint of hydrogen, and thus the value of its use in reducing the economy's greenhouse gas emissions**. In fact, if we imagine that the transport and distribution of hydrogen generate leaks similar to those in gas networks (between 0.5 and 3% of leaks), then this would represent a footprint of 0.006 to 0.030 $kgCO_2e$ / $kgH_2$, to be compared with the carbon footprint of low-carbon hydrogen production, 3 $kgCO_2e$ / $kgH_2$. If this warming effect seems to be limited, it should be kept in mind that the lifetime of hydrogen in the atmosphere is short and that its warming power over 20 years would be about 30 times that of carbon dioxide over the same period (Warwick, Griffiths, Keeble, Alexander Archibald, & Shine). If necessary, it would be relevant to integrate this impact, especially in the cases where hydrogen transport is envisaged. However, we must keep in mind the scientific doubts that have not yet been resolved as well as the loss rates in hydrogen networks that may be lower than those of methane, because the safety constraints are stronger for hydrogen and the molecule is more precious, two reasons that lead us to be much more attentive to leaks in the networks. In addition, there are many cases of use for which hydrogen will be produced close to its place of use, therefore without the need to transport the molecule.

# What is hydrogen used for today?

Although many announcements focus on the use of hydrogen as an energy carrier, **most of the hydrogen is currently used as a reagent in the industrial sector**. It is currently consumed worldwide at **about 115 $MtH_2$** (2018 value), and the recent trend is a small but steady growth since the 2000s, at a rate of +3% per year.

**Petrochemicals alone account for more than 70% of hydrogen use worldwide, with:**

- **Refineries**, which use it primarily for crude oil desulfurization and for hydrocracking to transform heavy crude products into higher value products. Hydrogen is also used in smaller volumes for deoxygenation of biofuels;
- **The production of ammonia** ($NH_3$) with the Haber-Bosch process. About 80% of the ammonia produced is then used in the production of fertilizers such as ammonium nitrate. The remainder is used for industrial applications such as explosives, synthetic fibers and other special materials;
- **The production of methanol**, which is then used in a wide range of industrial applications, including the production of formaldehyde, methyl methacrylate and various solvents;
- **The production of hydrogen peroxide, cyclohexane** or other molecules in the chemical industry that require pure hydrogen.

[9] This study was not published in a peer-reviewed scientific journal.

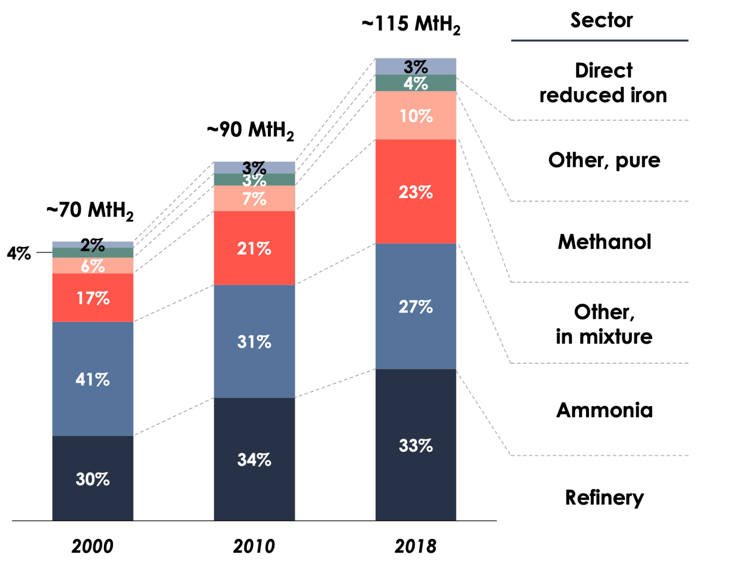
**Metallurgy represents about 3% of hydrogen consumption, with:**

- **Direct reduction of iron ore** using hydrogen mixed with carbon monoxide (called Coke oven gas or syngas as a reducing agent. This represents 7% of the primary steel production in the world;
- Other uses requiring pure hydrogen such as **welding** or certain **surface treatments**.

**The production of heat and, to a lesser extent, electricity, represents more than 20% of the uses of hydrogen on the sites listed above.** These uses use hydrogen in a mixture, co-produced in the form of flue gas at steel mills and gases derived from steam crackers at refineries.

Finally, hydrogen is used pure for other **diffuse uses such as electronics** (semi-conductors), **glass**, **food** or even **transport** (in a very marginal way).

**Evolution of hydrogen demand in the world since 2000 by sector** ($MtH_2$)




*Source : (IEA, 2019).*

# Hydrogen is today mainly produced from fossil sources, so it has a high carbon footprint

It is **inappropriate to talk about dihydrogen as an energy source**: by "energy source" we mean a naturally present and exploitable energy, such as oil, coal, natural gas or wind. **Hydrogen is in fact an energy carrier**: this gas is almost never present in a form that can be directly used on our planet (the case of the Malian deposit in Bourakébougou is known but is an exception). **The hydrogen consumed must therefore be produced by using energy to separate the hydrogen from a molecule that contains it: water** ($H_2O$) **or methane** ($CH_4$) for example.

**In the hydrogen market, it is important to distinguish dedicated production from co-production**, since some industrial processes co-produce hydrogen. For example:

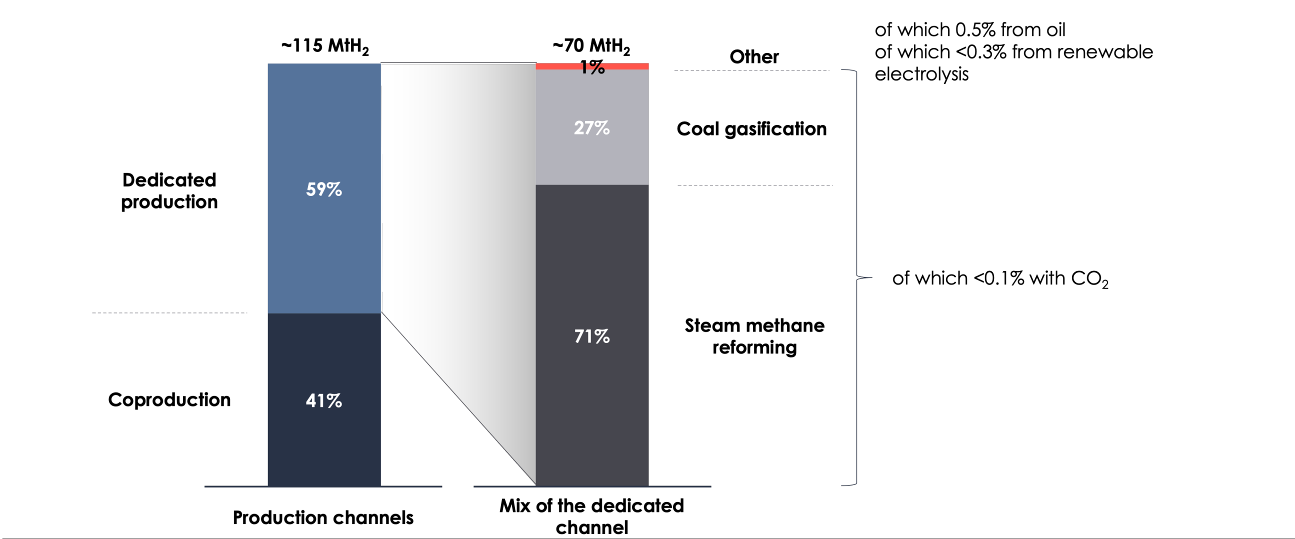
- In steel mills: hydrogen is present in Coke oven gases;
- In refineries: hydrogen is produced during the steam cracking process;
- For chlorine production: the chlor-alkali process, which aims to produce chlorine gas and sodium hydroxide by electrolysis of brine, also produces hydrogen.

The hydrogen thus co-produced is used directly on site (as a reagent or for heat production) or resold to nearby industrial sites in the case of petrochemical complexes.

Worldwide in 2018, **less than 60% of the hydrogen used came from dedicated production channels, and almost entirely from fossil resources**. **Coal gasification and especially steam reforming of natural gas represented more than 99% of dedicated hydrogen production**. Among the remaining of the dedicated production, we can quote the oxidation of heavy hydrocarbons (0.5%) and electrolysis (< 0.3%).

It is **this process of electrolysis which is much talked about in the announcements** around hydrogen, because it **gives rise to much hope**. Electrolysis consists in the **separation of the dihydrogen molecule and the oxygen atom which compose the water molecule**, following the reaction: $2H_2O \rightarrow 2H_2 + O_2$. This decomposition reaction is produced thanks to an activation by an electric current.

**Global hydrogen production in 2018 by pathway** ($MtH_2$) **and dedicated pathway production mix**




*Source : (IEA, 2019).*

The production cost and carbon footprint of hydrogen is highly dependent on how it is produced. As shown in the table below from a **literature** review (Parkinson et al., 2019)**.** As shown in the table below from a literature review, **production costs range from €1 to €13 per kg of hydrogen**, while **the carbon footprint of its production ranges from 0.5 to 22 $kgCO_2e$ per kg of hydrogen**. Electrolysis using low-carbon electricity has a carbon footprint ranging from 0.5 to 3 $kgCO_2e$ per kg of hydrogen, while fossil fuel processes can go up to about 22 $kgCO_2e$ per kg of hydrogen in the case of coal gasification. **Unfortunately, the most carbon-intensive processes are currently the least expensive.**

It is interesting to note that **the carbon footprint of hydrogen from steam methane reformation, the most common process, is 13 kgCO₂e per kg of hydrogen** according to the literature review. However, the figure of 10 kgCO₂e per kg of hydrogen is still widely found in the literature on hydrogen. This underlines the importance of **reasoning in terms of carbon footprint: the impact on the climate of hydrogen production does not only depend on the direct emissions of the production processes (in which case hydrogen produced by electrolysis would have zero emissions), but also on the upstream emissions to produce the electricity or the molecule from which hydrogen is derived**. In the case of steam methane reforming, the emissions from the upstream of the gas chain are very significant.

**Carbon footprint and costs of different hydrogen production processes: Global perspectives from a meta-analysis**

| Category in the French regulation[1] | Description | Carbon footprint[2] ($kgCO_2e$ / $kgH_2$) Upstream em. | Direct em. | Cost[2] | Market share[3] |
|---|---|---|---|---|---|
| Renewable $H_2$ | $H_2$ produced by electrolysis of water **from renewable electricity** or by another technology using a renewable source. | 0,5 - 3 | - | ~4 to 13 € / $kgH_2$ | <0,3% |
| Low-carbon $H_2$ - Nuclear | The $H_2$ whose production **generates less GHG than the threshold[4] for renewable energy.** *Here from **nuclear** electricity.* | ~1 | - | ~6 € / $kgH_2$ | <1% |
| Low-carbon $H_2$ - Fossil with CCS | The $H_2$ whose production **generates less GHG than the threshold retained for the renewable.** *Here from fossil resources with **Carbon Capture and Sequestration.*** | ~5[5] | with 90% capture : ~1 | ~2 € / $kgH_2$ | <0,1% |
| Carbon intensive $H_2$ - Natural gas | $H_2$ which **is neither low-carbon nor renewable.** Mainly produced from **fossil resources.** *Here by steam reforming of methane.* | ~5[5] | ~8 | ~1 € / $kgH_2$ | 71% |
| Carbon intensive $H_2$ - Charcoal | $H_2$ which **is neither low-carbon nor renewable.** Mainly produced from **fossil resources.** *Here by gasification of coal.* | ~2 | ~20 | ~1 € / $kgH_2$ | 27% |

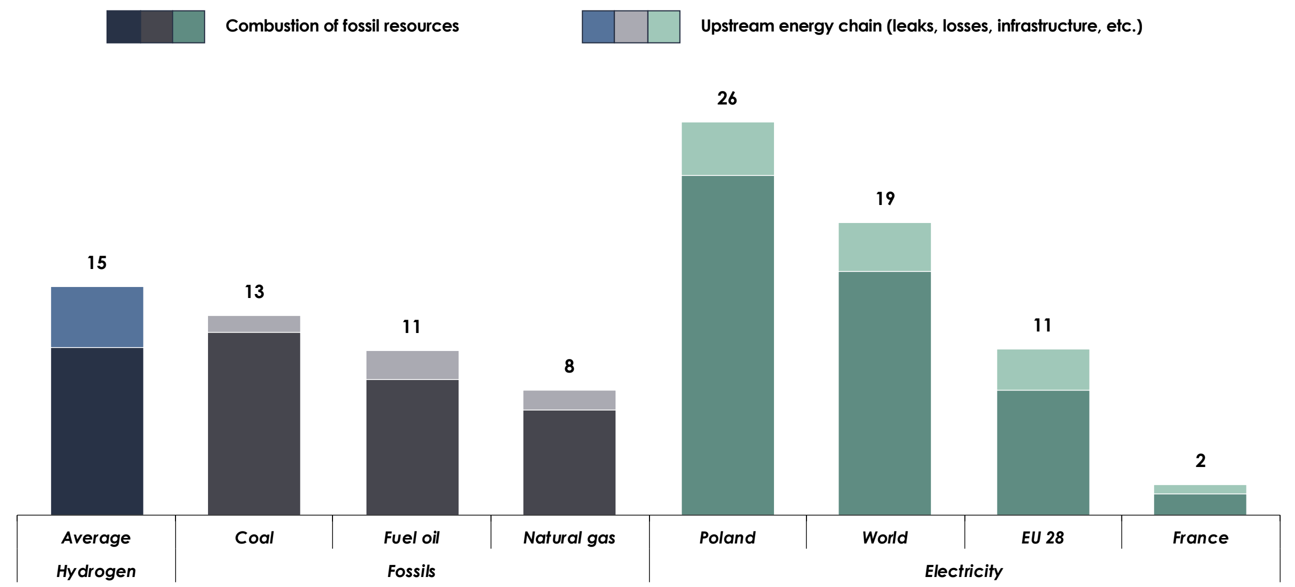
*Notes and sources: (1) Ordinance No. 2021-167 of February 17, 2021 on hydrogen | (2) Based on the study "Levelized cost of $CO_2$ mitigation from hydrogen production routes." (Parkinson et al., 2019) The term carbon footprint means that emissions are accounted on the whole life cycle. | (3) For dedicated production, according to (IEA, 2019) |(4) Threshold to be defined by decree. Namely, according to the European Taxonomy the sustainability criterion for $H_2$ is to respect a cap of 3 $kgCO_2e$ / $kgH_2$ | (5) Possible overestimation for gas which takes into account "the whole supply chain, including low pressure distribution, which is unlikely to be part of the hydrogen supply chain".*

**Being mostly of fossil origin, hydrogen has a very high carbon footprint, with a worldwide average of 15 $kgCO_2e$ / $kgH_2$ for dedicated hydrogen production[10]. In** comparison, the same amount of energy in the form of coal represents 13 $kgCO_2$ e, 11 $kgCO_2e$ for fuel oil and 8 $kgCO_2e$ for natural gas. The same energy in the form of electricity has a carbon footprint that varies according to the electricity generation mix[11]. It would be 26 $kgCO_2e$ for the Polish electricity mix, but only 2 $kgCO_2e$

[10] This average is derived from carbon footprints from (Parkinson, Balcombe, Speirs, Hawkes, & Hellgardt, 2018)combined with market shares by pathway for dedicated hydrogen production from (IEA, 2019).
[11] As part of these comparisons, we consider the energy content of the different fuels (coal, oil or gas) or the energy equivalence for electricity (1 kWh of electricity equals 1 kWh of hydrogen).

in the French case. **As currently produced, hydrogen is therefore among the energy carriers with the highest carbon footprints**.

**Carbon footprint of different energy carriers today** (kg$CO_2$e / kg$H_2$ equivalent)




*Notes: [1] The term carbon footprint means that emissions are accounted on the whole life cycle. | [2] Equivalence between vectors is based on the same amount of energy (LHV), defined as the energy content of 1 kg of hydrogen, i.e. 33.6 kWh.*
*Sources: Hydrogen: Carbone 4 from Parkinson et al. Fossil fuels: ADEME carbon base Electricity: ADEME carbon base (France) and Carbone 4 from IPCC and IEA (outside France)*

**Reducing the carbon footprint of hydrogen production is possible, but not without additional costs**. By combining costs and carbon footprint for hydrogen production in the table above, we find that **abatement costs for the production phase alone are around €125 / t$CO_2$e in the case of blue hydrogen** (produced from fossil energy with $CO_2$ capture and storage) which reduces the carbon footprint by two compared to hydrogen produced from steam methane reforming, **and up to a few hundred euros per t$CO_2$e in the case of hydrogen by electrolysis**, which allows for greater reductions in the carbon footprint.

# Electrolysis allows the production of low-carbon hydrogen, if the electricity is itself low-carbon

**Hydrogen produced by electrolysis is not necessarily synonymous with low carbon hydrogen.** If the electricity mix is largely fossil, it is more emissive to use hydrogen production by electrolysis than the direct use of fossil resources.

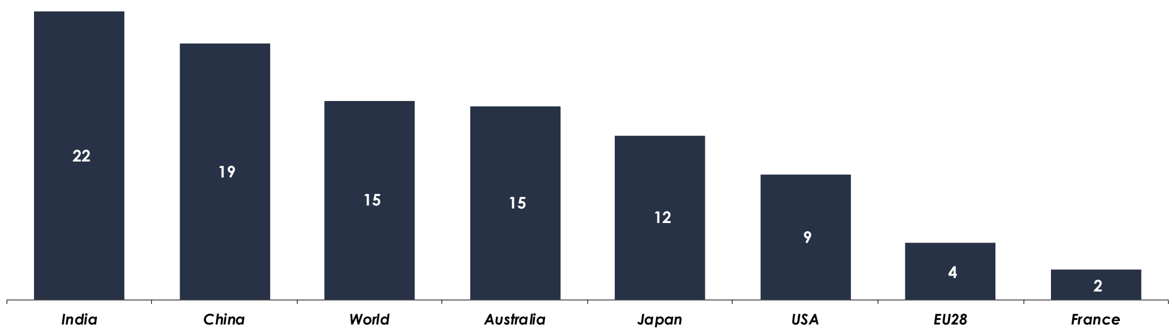
*What is low-carbon hydrogen?*

**We have used the carbon footprint threshold of the European Taxonomy** (this threshold is likely to be replicated in the French regulations). Thus, **hydrogen is here considered low-carbon if and only if its carbon footprint is less than or equal to 3 kgCO2e / kgH2.**

**To be low-carbon, hydrogen by electrolysis must be produced from electricity with a carbon content lower than 60 g$CO_2$e / kWh**, taking into account the current efficiency of electrolyzers. This **corresponds to the carbon intensity of the current French electricity mix**. But **currently in Europe, few countries have a national electricity mix that is compatible with low-carbon hydrogen production**: Norway, France, Sweden and even Switzerland have electricity mixes that are sufficiently low in carbon to produce low-carbon hydrogen; however, **on average in Europe, hydrogen is just as carbon-intensive as the average hydrogen production mix from fossil sources**. Finally, in countries like Germany or Poland, hydrogen is respectively 2 and 3 times more carbon intensive if it is produced from electricity.

In a scenario where countries respect the Paris Agreement and strongly decarbonize their electricity mix, the production of hydrogen through electrolysis would remain on average in the world as carbon intensive as hydrogen from fossil sources in 2030.

**Emissions related to hydrogen production by electrolysis in 2030 according to the origin of the electricity** (kg$CO_2$e / kg$H_2$)




*Notes: [1] Emissions are accounted on the whole life cycle. | [2] According to ADEME, the carbon footprint of an electrolyzer is 38 g$CO_2$e / kg$H_2$: it is therefore not represented on the graph above.*
*Sources: Carbone 4 based on the EPP and the SNBC (France) and the IEA - WEO - SDS scenario (outside France).*

# Current and future costs for low-carbon hydrogen

In the most optimistic projections on hydrogen production costs, it is not uncommon to see hydrogen reaching the threshold of 2 € / $kgH_2$ , facilitating the substitution of carbon intensive hydrogen. **Currently, the production cost of hydrogen by electrolysis varies between 3 and 5 € / $kgH_2$ under very favorable conditions**: for example, operation for at least 4,000 h / year, an electricity cost of about 50 € / MWh[12] and a yield of 63% to reach a price of 5 € / $kgH_2$; or operation for 7,000 h / year with electricity at 40 € / MWh in an even more optimistic scenario to reach a price of 3 € / $kgH_2$ (with the same yield assumption).

In our study, **we modeled the cost of producing hydrogen by electrolysis in 2030 under two schemes**:

- **Centralized production**: electrolyzers benefit from a fixed price of electricity for a large part of the year, which allows to amortize the CAPEX of the electrolyzer and the connection to the network;
- **Decentralized production**: hydrogen production from renewable wind and photovoltaic electricity sources in favorable areas because of high wind or sunshine, and hydrogen transport to the place of consumption in Europe. For illustrative purposes, and without trying to investigate the plausibility in terms of feasibility or the desirability of such situations, we have considered the production of hydrogen from solar photovoltaic in North Africa, or from offshore wind in the North Sea, purely from the point of view of production cost. In this scheme, the electrolyzer benefits from very cheap electricity but has a lower operating time in the year, which corresponds to the load factor of renewable electricity installations.

In both schemes, taking into account the decrease of the CAPEX of the electrolyzers and the improvement of their yields, we arrive at **prospective costs of hydrogen production between 3 and 4 € per kg of hydrogen, which is not enough to make low-carbon hydrogen competitive compared to the 1 € per kg of hydrogen produced from fossil sources**, in the hypothesis of prices similar to those of 2021. The recent surge in the price of gas, which has exceeded €100/MWh, could change the order of merit: one kg of hydrogen produced from natural gas would cost around €5, while the one produced via an electrolyzer would oscillate between €3 and €14, depending on the price at which electricity is purchased[13].

One must therefore keep in mind that economic analyses, *especially* when they concern energy, are always fraught with uncertainty because of the price assumptions used.

[12] This may seem low in light of the dramatic rise in European electricity prices since the end of 2021, but was previously a reasonable level for a forward price in the wholesale electricity market.
13 https://www.spglobal.com/commodityinsights/en/market-insights/topics/hydrogen ; https://www.sgh2energy.com/economics ; https://www.rechargenews.com/energy-transition/green-hydrogen-now-cheaper-to-produce-than-grey-h2-across-europe-due-to-high-fossil-gas-prices/2-1-1098104

**For the rest of the study**, we have considered a **prospective production cost** value **of 3.4 € per kg of low-carbon hydrogen[14] by 2030**, corresponding to a **carbon footprint of 3 kg$CO_2$e per kg of hydrogen.** This translates an **average abatement cost** compared to fossil hydrogen production **of about 200 € / t$CO_2$e.**

[14] This would correspond to an operation on grid electricity at 50 € / MWh for 6 000 h / year, or to an operation with electricity from offshore wind at 36 € / MWh with a load factor corresponding to 4 000 h / year. The sensitivity to the cost of electricity is very high: about 70% in the first case and nearly 55% in the second.

# III - What are the prospects for hydrogen consumption?

## Presentation of the general modelling framework

The objective of this study is to enlighten **the most efficient uses of low-carbon hydrogen to respond to the climate emergency**. In this regard, we will wonder:

- In what proportion can low-carbon hydrogen decarbonize[15] the studied uses? More precisely, the evaluation aims at expressing the **unitary decarbonization power**[16] of low-carbon hydrogen;
- What is **the comparative advantage of low-carbon hydrogen in the studied uses**, considering other decarbonizing options?
- If low-carbon hydrogen comes out on top in the previous assessment, what is the **volume that needs to be mobilized in the studied use for the sector in question to be aligned with the climate goals of the Paris Agreement**?

### *Characteristics of the low-carbon hydrogen considered*

In this study, the modelling assumes that low-carbon hydrogen is used in the sense of the European Taxonomy. In a conservative approach we have chosen to use the threshold value in question, and not a lower value, i.e. a **carbon footprint of 3 $kgCO_2e$ / $kgH_2$** for low-carbon hydrogen.

The **production cost of hydrogen**, when needed for economic evaluations, is assumed to be **€3.4 per kg of hydrogen**. This value is based on prospective modelling to 2030 taking into account the investment and operating costs of electrolyzers, as developed in the previous section.

### *Scope of uses covered in this study*

We considered a set of **11 possible uses of hydrogen, divided into 3 sectors**, as represented in the table below:

[15] Decarbonization, or "decarbonizing," refers to the ability to reduce greenhouse gas emissions.
[16] The unitary decarbonization power is the proportion of carbon footprint reduction that low-carbon hydrogen allows within a given use. It is said to be "unitary" in the sense that the decarbonization is related to a volume of activity of the underlying studied: for example, decarbonization per ton of steel for the steel industry, or decarbonization per km driven for trucks.

| Industry | Transportation | Energy |
| --- | --- | --- |
| Ammonia production | Sea | Mixed consumption in gas networks |
| Methanol production | Air | Storage for the electrical system |
| Steel production | Road: trucks | Refining |
| Heat use | Railway | |

Uses selection of this study relies on the one hand on **the uses that are most often concerned by the announcements and strategies of the public authorities** (e.g. steel, aviation, railways, etc.), and on the other hand **on the basis of existing studies**[17] which have looked at the relevance of hydrogen according to uses, taking into account the decarbonizing alternatives.

**As far as the use of light vehicles is concerned** (vans but especially cars), we have **chosen not to study the use of low-carbon hydrogen**, because a consensus seems to be forming on the fact that **this is not the decarbonization option that is likely to develop significantly within these segments**. A certain area of relevance is obviously possible, for example for cabs, for captive fleets of companies with high daily mileage, or even in the form of hybridization within a vehicle between battery and hydrogen. However, **the decarbonization option via battery electric vehicles seems to have won out in actual short-term deployments**[18].

### *Approach*

As presented at the beginning of this chapter, **the study of a potential use of low-carbon hydrogen begins with the evaluation of its relevance** based on:

- **Its unit decarbonization power**;
- **Its comparative advantages or disadvantages compared to other decarbonizing options**. This can be assessed based on the unitary decarbonization power of the different decarbonization options available, their respective economic cost, but also other qualitative assessment criteria (for example technical limitations, or inertia in the diffusion of decarbonizing solutions).

Then, we determined **potential volumes of low-carbon hydrogen use for different uses studied**.

If low-carbon hydrogen is relevant for the use considered, it is **sometimes possible to determine potential volumes in a normative way**[19] for this use. This can be done provided that there are specific emission reduction targets for this use that are aligned with the climate ambition of this

[17] For example (IDDRI, 2022) and (Agora Energiewende, 2022).

[18] According to (Nature, 2022), there were about 25,000 hydrogen cars in the world's automobile fleet at the beginning of 2021, 90% of which were concentrated in four countries: Korea, the United States, China and Japan. Moreover, there were only 2 car models in the ranges of global car manufacturers. While at the time of writing, there are about 15 million battery-electric and plug-in hybrid cars in the world, and almost all global manufacturers have models in their lineups (at least 350 models available globally).

[19] Modelling is normative when the result obtained is the result of the application of "constraints" on the modeled system. In our case, the constraint is to respect a trajectory of greenhouse gas emissions reduction for the use or the sector concerned, a trajectory that is derived from a more global scenario that respects the carbon budget of the economy in order to limit global warming to 2°C or even 1.5°C. The scenarios used that show carbon budgets are those of the International Energy Agency (IEA): depending on the case, we have considered either scenarios from the Energy Technology Perspectives family or from the World Energy Outlook.

study, i.e. compliance with the Paris Agreement (less than 2°C of warming, or even 1.5°C). The uses for which we were able to arrive at these normative potentials are:

- The ammonia production;
- The methanol production;
- The steel production;
- The maritime sector;
- The airline sector.

For other uses, potential volumes were determined in different ways:

- For refining: the evaluation of the potential low-carbon hydrogen volumes is not based on a decarbonization objective for the sector, but on a projection of all the hydrogen consumption that is not self-produced by the sector, in a scenario of decarbonization of the world economy, therefore with less consumption of petroleum products but more biofuels. The model also takes into account the possible evolution of fuel desulfurization standards, and the refinery supply mix between heavier and lighter crude oils;
- For trucks: in this use where many decarbonizing alternatives exist, the evaluation of the relevance of low-carbon hydrogen has led to an estimation of the potential volume in order of magnitude with a simplified modelling;
- For mixed consumption in gas networks: the relevance assessment led to not estimating the potential volume of low-carbon hydrogen;
- For railways and industrial heat: for these two uses, which were not given priority in the study, we have taken a potential volume from another study;
- Finally, for the storage of the electrical system: this use of hydrogen does not directly lead to a reduction in emissions, but it is a facilitating condition, even necessary for the development of certain renewable electrical production methods. Thus, the modelling has also led to an estimation of the potential volume of low-carbon hydrogen in a normative way, not according to emission reduction objectives, but to a scenario of deployment of renewable energies in the global electricity mix of a 1.5°C scenario.

Finally, beyond the evaluation of relevance and the determination of potential volumes use by use, the **great interest of the study lies in the last step which is to proceed with an inter-use or inter-sector analysis to conclude an order of merit for the use of low-carbon hydrogen among the different uses studied**. This analysis is based on the **decarbonizing intensity of hydrogen**: this metric, expressed in $tCO_2e$ / $tH_2$, translates **the reduction of the carbon footprint (expressed in $tCO_2e$) of a use that low-carbon hydrogen allows, compared to one unit of hydrogen (expressed in $tH_2$)**.

# What are the prospects for hydrogen in the industry?

**Currently, most hydrogen is used in industry**, as a reagent and entirely from fossil sources. Therefore, it seems both **a necessity and a priority to replace this fossil hydrogen with low-carbon hydrogen in order to decarbonize these uses for which few other levers exist**.

## Ammonia and methanol production

*Ammonia production today: usage, hydrogen consumption and carbon footprint*

Ammonia, or $NH_3$, is the largest consumer of hydrogen in the chemical sector, accounting for more than a quarter of global hydrogen end-use at 31 $MtH_2$ in 2018 (IEA, 2019). **More than 80% of ammonia is currently used for the production of synthetic fertilizers for agriculture**. Ammonia is **produced entirely from fossil hydrogen**, mainly by steam reforming of methane in France and Europe (Fuel Cells & Hydrogen Observatory, 2021). It is then combined with nitrogen via the Haber-Bosch process. This process requires 180 $kgH_2$ / $tNH_3$[20] and its direct emissions vary from 1.6 to 2.7 $tCO_2e$ / $tNH_3$ depending on the energy efficiency of the different plants and the source of hydrogen production, with a world average of around 2.4 $tCO_2e$ / $tNH_3$ (IEA, 2019). **Hydrogen production accounts for almost 80% of the carbon footprint of ammonia**, the rest being due to HaberBosch's -energy-intensive process-, mainly obtained by burning natural gas.

*Methanol production today: usage, hydrogen consumption and carbon footprint*

Methanol, or $CH_3OH$, is the second largest consumer of hydrogen in the chemical sector with nearly 12 $MtH_2$ consumed in 2018. **Methanol is used in many applications: mainly as a reagent in the synthesis of other chemicals**[21] (55% of global demand) but **also as a fuel** (EY for AFHYPAC, 2020). Methanol is also **produced entirely from fossil hydrogen**, mainly by steam reforming of methane in France and Europe (Fuel Cells & Hydrogen Observatory, 2021). It is then recombined in the methanolation process. This process requires 130 $kgH_2$ / $tCH_3O$[22] and its direct emissions vary from 0.8 to 3.1 $tCO_2e$ / $tCH_3OH$ depending on the energy efficiency of the different plants and the source of hydrogen production, with a world average of around 2.3 $tCO_2e$ / $tCH_3OH$ (IEA, 2019). **Hydrogen production accounts for nearly 50% of the carbon footprint of methanol**.

*Ammonia and methanol production tomorrow: the role of low-carbon hydrogen*

Due to the growing population and an agricultural model that relies heavily on the use of ammonia-based nitrogen fertilizers to feed it, the IEA's prospective analyses result in an **increase**

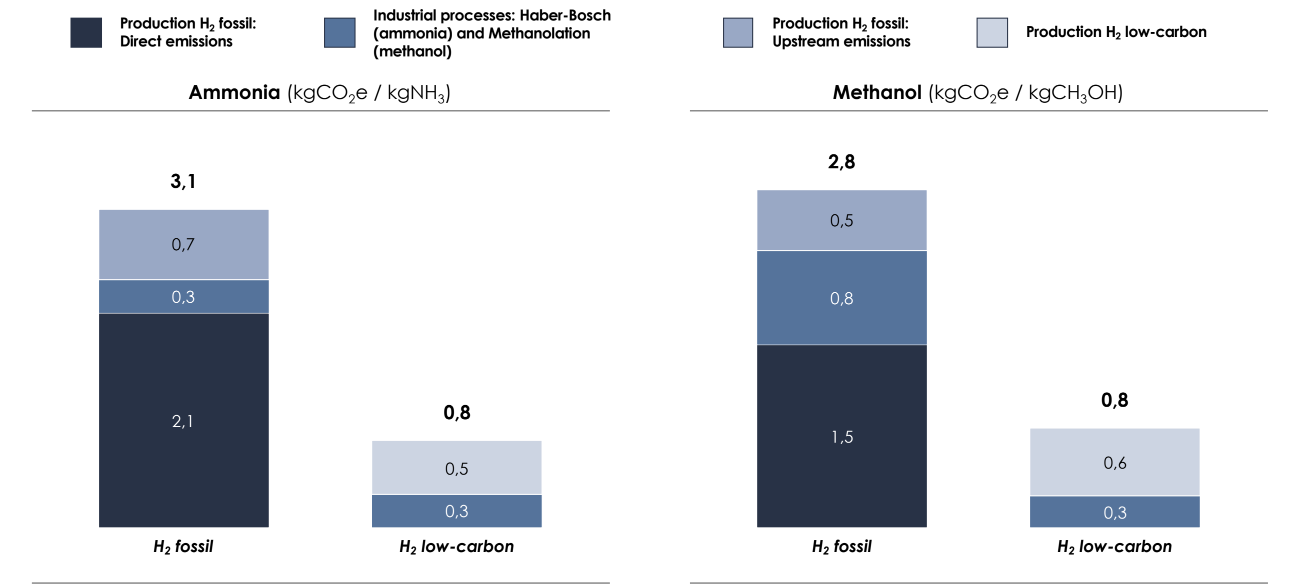
[20] In France and Europe, 5 to 10% of this hydrogen is co-produced and comes from nearby industrial sites.
[21] About 40% of methanol is converted to formaldehyde, which is then processed into products as diverse as plastics, synthetic resins (some of which are used to make plywood), paints, explosives and wrinkle-free fabrics.
[22] In France, 3% of this hydrogen is co-produced and comes from nearby industrial sites.

**in ammonia consumption of 1.2% per year by 2030**. According to the IEA, **the demand for methanol will grow at a higher rate of 3% per year until 2030** (IEA, 2018). **However, global emissions from the chemical sector are expected to increase by only 0.3% per year over the same period** according to the same IEA scenario (IEA, 2018), which is compatible with a temperature rise lower than 2°C.

-Given the structure of the sector's emissions, the most important stage to decarbonize is hydrogen production, for which conversion to low-carbon hydrogen produced by electrolysis is an effective solution: **the low-carbon hydrogen pathway has a unitary decarbonization potential of around 65% in emissions related to direct energy consumption** (in situ combustion and upstream for the production of electricity consumed) and **70% in footprint compared to the fossil pathway for the production of these two primary chemicals**.

The production of methanol by the low-carbon route is different than the traditional route: it consumes decarbonized electricity to capture $CO_2$ directly into the atmosphere, biogenic or even from other industries. As the reaction is not the same, it requires a greater quantity of hydrogen (+50%) for the same quantity of methanol produced.

**Carbon footprint of fossil and low-carbon hydrogen production routes**




In order for the ammonia and methanol production sectors to respect a greenhouse gas emissions evolution that is compatible with the Paris Agreement while following the growth of the activity, **low-carbon hydrogen** would have to be **massively mobilized** if it is the main decarbonization lever chosen. In other words, this scenario would require a 12% penetration of the sector by low-carbon hydrogen in the case of ammonia and 50% in the case of methanol in less than 10 years, i.e. **for ammonia and methanol respectively 5 $MtH_2$ and 10 $MtH_2$ of low-carbon hydrogen in 2030**. If such penetrations of low-carbon hydrogen are not achieved, it is the volume of the sector's activities that should be questioned - unless the overrun of the sector's carbon budget can be absorbed by another sector's outperformance of its own carbon budget?

**CCS[23] is another potential pathway to reduce emissions from ammonia and methanol production, with comparable emission reductions**. From a cross-industry perspective, CCS is most likely to be used for these types of facilities because the flue gases are concentrated in $CO_2$, which facilitates its capture. Moreover, since production sites have historically developed near hydrocarbon extraction areas, they are likely to be relevant candidates for $CO_2$ storage (old hydrocarbon deposits can in some cases be used to store $CO_2$).

In conclusion, **low-carbon hydrogen is an important and efficient lever for decarbonization of these two sectors**, and even seems to be one of the only ones with CCS. However, **a strong penetration of low-carbon hydrogen and CCS would be necessary to reconcile the carbon budget and the activity growth hypotheses for these sectors, which raises questions about the plausibility of these carbon budgets with respect to activity projections, or vice versa**.

## Steel industry

*Steel today: usage, hydrogen consumption and carbon footprint*

The steel industry **today consumes hydrogen in a mixture in two different ways**:

- **In the most common route for steel production, the BF** blast furnace **- BOF**[24] (which accounts for more than 70% of the world's steel production) which consumes on site the hydrogen co-produced in the form of Coke oven gas (mixed with carbon monoxide). This hydrogen is mainly used for the production of heat and more rarely for electricity;
- **For production by the DRI process[25] known as "gas-based"** (which represents 7% of world steel production in 2020) which consumes about 4 $MtH_2$ per year in 2018. In this process, a gas mixture containing hydrogen and carbon monoxide is used to reduce the iron ore. The hydrogen is in variable proportions: 25% to 60% hydrogen, depending on the process and the source of production of the synthesis gas (mainly from natural gas or coal) and the degree of purification.

**The third main route of steel production is the recycling route**, which accounts for about 20% of the world's steel production. In this route, scrap is transformed into steel in *electric* arc furnaces (*EAF*). This method of steel production does not use hydrogen.

The different steel production routes have very different carbon footprints, ranging from 2 $tCO_2e$ per ton of steel for the BF-BOF route to 0.5 $tCO_2e$ per ton of steel for the recycling route. In between, the DRI gas-based route emits about 1.4 $tCO_2e$ per ton of steel.

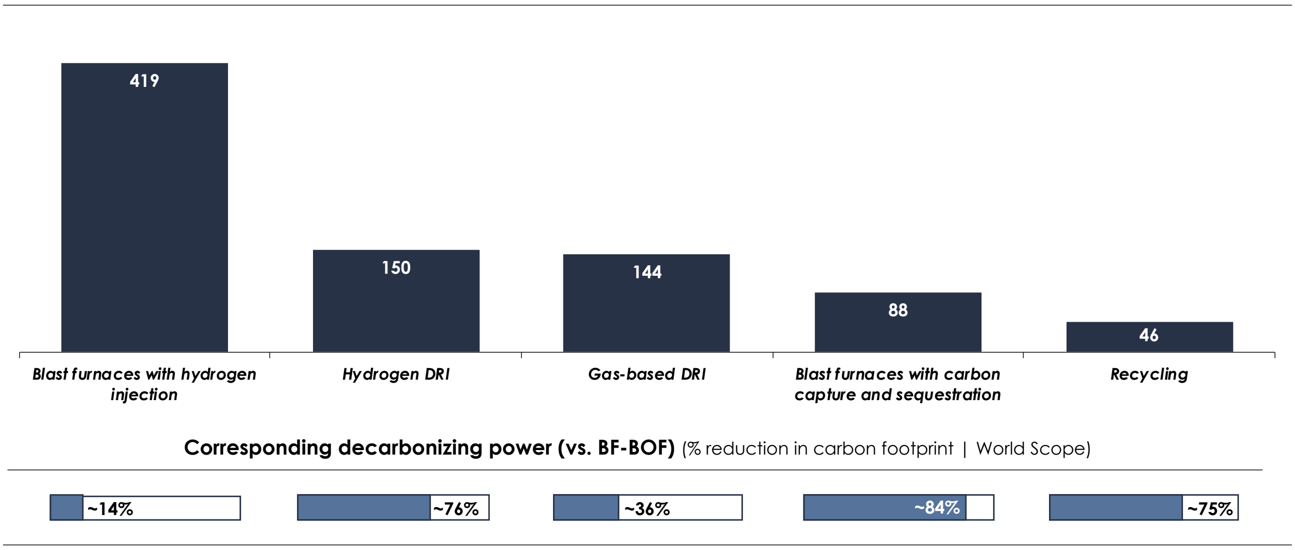
*The steel of tomorrow: the role of low-carbon hydrogen*

In the IEA's Beyond 2 Degrees scenario (IEA, 2017), **steel demand is stable through 2030 but its emissions decline at a rate of 4% per year between the current period and 2030**. This refers to direct on-site emissions and direct emissions from power generation for steel. **Several**

[23] Carbon capture and sequestration (CCS) in ammonia or methanol production leads to a decrease in emissions similar than the substitution of fossil hydrogen by low-carbon hydrogen considered here. The conclusions we draw for low-carbon $H_2$ would therefore be the same for CCS.
[24] BF-BOF = Blast furnace - Basic Oxygen Furnace
[25] DRI = Direct Reduced Iron, direct reduction of iron ore in French.

**decarbonization levers** are possible for the industry: increasing the proportion of **recycled steel** in the production mix, increasing the **gas-based DRI pathway** in primary production, **injecting hydrogen as an auxiliary reductant in** blast furnace, producing steel by the **hydrogen only DRI pathway,** and finally **carbon capture and sequestration**. We have studied these pathways according to their decarbonization potential and cost:

**Abatement cost (vs. BF-BOF) by different steel production pathways by 2030** ($ / $tCO_2e$)




**As far as low-carbon hydrogen is concerned, it appears that its use in the steel sector is relevant for the hydrogen DRI pathway but not for direct injection of hydrogen into blast furnaces, which reduces emissions to a small extent but has a high abatement cost**. Moreover, **even if hydrogen DRI seems promising, it is less so than the increase of the recycling pathway in the production mix or the development of CCS on blast furnaces, especially on the economic aspect**. Finally, although the development of hydrogen-fueled DRI is on the roadmap of many producers, **it is unlikely that this pathway will represent a large share of the mix by 2030 given the development timeframe**[26].

**Increasing the rate of steel recycling is therefore the priority lever** for the sector and this avenue has great potential: it currently covers only 20% of needs and even if the collection of scrap metal to feed the sector remains a challenge, there should be no major obstacle to reaching collection levels that can satisfy 70% of steel demand by 2050 (Carbon 4, 2019). With this perspective, taking into account the inertia in the development of a collection and recycling sector leads us to consider that the 30% threshold could be reached by the sector by 2030.

**The gas-fired DRI pathway has been growing strongly** since 2015 (+8% per year) and could reach approximately 20% of the overall production mix by 2030 if the trend continues. However, producer announcements suggest that a small share of this production (< 5%) could be taken up by the hydrogen only DRI pathway (see previous note on large steel company announcements).

[26] French steelmaker ArcelorMittal announced the opening of its first DRI steel plant in Sestao in 2025, which is expected to produce 1.6 Mt of steel. Germany's ThyssenKrupp announced the commissioning of its first hydrogen DRI plant in 2025 with a target production of 3 Mt of steel in 2030. Finally, the Swedish company SSAB has announced the commercialization of steel produced with $H_2$ DRI technology in 2026, with a target of 2.7 Mt of steel in 2030 (HYBRIT project), and a demonstrator in 2025. Given the timing of these announcements and the inertia of the transformation of the production system, the volumes marketed will still be low in 2030.

**Thus, in 2030, half of the world's production will probably rely on the BF-BOF sector, which will therefore have to use CCS in a significant way (about 15%) or reduce the volumes produced in order to meet the sector's ambitions in terms of emission reductions.**

In conclusion, the volumes of hydrogen mobilized by the sector are tending to increase, with the main driver being the development of the gas-fired DRI route, which will mobilize about 10 million tons of hydrogen overall. The BF-BOF route, although currently the second largest consumer in the sector with about 5 $MtH_2$ per year, will use the hydrogen it co-produces (some 10 million tons per year). The remainder could be recovered through industrial synergies within the sector for gas-fired DRI or in other applications such as chemical production[27]. Finally, **hydrogen-fired DRI, which is just beginning to be developed on a large scale, will probably not consume more than 3 $MtH_2$. This route will likely have the greatest demand for access to low-carbon hydrogen to continue its development**.

## Industrial heat

*Industrial heat today: emissions and decarbonization pathways*

**Heat production accounts for nearly half of industry's emissions** (McKinsey, 2018), mostly from the combustion of fossil resources. In order to reduce emissions from this sector, and in addition to sufficiency and efficiency actions, the main levers concern the **shift of energy carrier to electricity, biomass, hydrogen and the installation of carbon capture and storage devices**. However, the latter option does not overcome dependence on fossil resources, requires storage sites close to industries, and may be more expensive than other options (McKinsey, 2018).

A recent study by the Hydrogen Council, a stakeholder supporting the development of hydrogen, concluded that **the use of hydrogen in this sector** will be **low in the near future (around 2 $MtH_2$ in 2030)** (Hydrogen Council, 2021), so this sector has not been analyzed in as much depth as the others.

*Industrial heat tomorrow: what place for hydrogen?*

**Industry has different types of heat requirements, which can be segmented into low temperature, medium temperature and high temperature**[28]. These heat levels are more or less compatible with the use of various alternative energy carriers.

**In the low-temperature segment, heat pumps are able to meet most needs**. Technically mature, economically competitive and much more energy efficient than other options, they seem to be the **main decarbonizing option for these temperature levels**. In addition, other technologies, such as renewable solar and geothermal energy, can be used to complete the energy mix and avoid the use of biomass.

[27] This co-produced hydrogen is currently used to produce heat or electricity on site but this use is not the most efficient. Considering its very high carbon footprint compared to other energy carriers, it could be judicious to use this hydrogen as a substitute for the currently fossil hydrogen needed for other uses (see 3.3).
[28] The thresholds usually shared to separate these segments are 100°C and 500°C.

**In the medium and high temperature segments**, heat pumps are not able to meet the needs, but all other options are possible. **Biomass is mature, but conflicts of use over the resource are a constraint**. On the other hand, low-carbon electricity will not be unlimited neither, especially for **options using hydrogen, which are globally less efficient than those using electricity directly** (Agora Energiewende, Agora Industry, 2021). However, in the case of industrial sites already using hydrogen for non-energy purposes, its use for heat can benefit from the existing infrastructure and appear as the most relevant option. Moreover, the alternative of direct electricity sometimes does not exist, especially for reaching a certain temperature and quality of flame, but **the combustion of hydrogen for high temperature applications still raises uncertainties in terms of technical mastery and respect of safety regulations** (ANCRE, 2021). We could then imagine prioritizing biomass for these segments. **Hydrogen does not show any particular advantage over its competitors**, so it is very unlikely that it will become the main decarbonization option for the sector.

# What are the prospects for hydrogen in transport?

**Currently, the volumes of hydrogen used in transportation are very limited**. There are only a few experiments or use as rocket fuel. However, **hydrogen could be used on a larger scale in two different ways:**

- **Directly, by combustion** (thermal engine) **or via a fuel cell** (electric engine);
- **Indirectly, as an intermediate reagent for the production of synthetic fuels** such as e-ammonia, e-methanol, e-LNG (Liquefied Natural Gas) or e-kerosene.

If it is low-carbon, hydrogen could be a lever for decarbonization in the transport sector, but it remains **in competition with other alternatives such as biofuels, electrification or biomethane**. It is therefore important to compare the relative performance of hydrogen with the different alternatives available depending on the transport segment studied and its specificities.

## Maritime

*The maritime sector today: carbon footprint and regulations*

The maritime sector currently emits over 1 billion tons of $CO_2e$ according to the International Maritime Organization (IMO, 2018) and there is an upward trend, driven by the projected increase in activity of +2.4% per year between 2022 and 2026 according to (UNCTAD, 2021).

**The IMO has recently set up several medium and long-term regulations to reduce the sector's impact on the climate**. Among them, the implementation of an increasingly restrictive threshold on the EEDI (Energy Efficiency Design Index) and the CII (Carbon Intensity Indicator), two indicators of energy and carbon performance assessed for each cargo ship, with sanction for those who would not follow it. As the CII is more ambitious than the sector's carbon budget (IEA, 2014), it is compatible with a growth in transported volumes with constant emissions. **These emission reductions concern the whole life cycle of fuels, from upstream to combustion, and are called *Well-to--Wake***. If this regulation is respected, the maritime sector's activity volumes could grow by 2.5% per year until 2030.

### *The maritime sector tomorrow: what alternative fuel choices?*

**In order to achieve this carbon intensity goal, it is necessary to shift from the fossil fuels currently used to alternative fuels**. We have studied three categories of fuels:

- **Fossil fuels**: HFO, VLSFO, MGO or LNG[29];
- **Synthetic fuels**, produced from hydrogen also called synfuels or e-fuels: e-methanol, e-ammonia, e-LNG, $LH_2$[30];
- **Bioenergy**: bioliquids, whether first generation (FAME diesel) or second generation (FAME or HVO)[31], and liquefied biomethane (BioLNG), first or second generation.

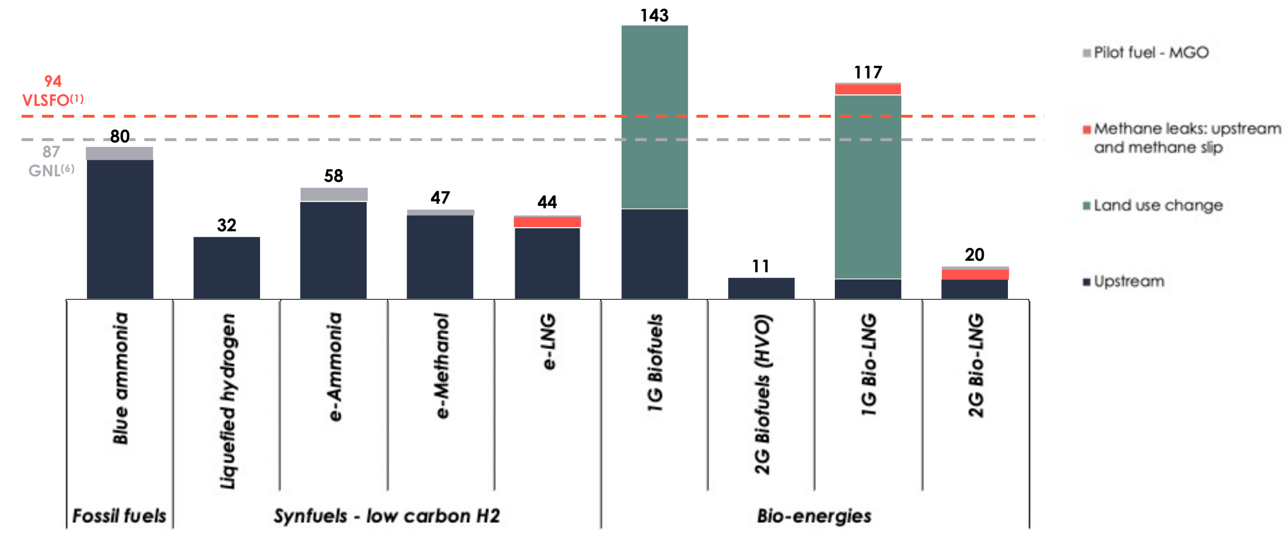
**The use of alternative fuels represents strong constraints for certain options**. Some of them have lower energy densities (mass and volume) than the fossil fuels currently used in the sector, which translates into **reductions in cargo carrying capacity for ships, due to the** additional space and mass for bunkers and fuel management systems on board. **To reflect this constraint, we reasoned with the notion of functional unit by calculating the costs and footprints of fuels relative to the same mass or volume carried**.

**In addition, some fuels require the use of additional pilot fuel to trigger combustion** (the equivalent of spark plugs in a gasoline car engine), which is generally a fossil fuel, in varying proportions. For example, in the case of ammonia, 7.5% of the energy consumption comes from MGO, a fossil fuel. **The emissions from the use of this pilot fuel** must therefore be considered.

**The integration of the space constraint and the pilot oil emissions leads to the use of a particular unit for the comparison: the fossil equivalent megajoule**[32]. This measures the *Well-to-Wake* carbon footprint (i.e., upstream to combustion) for the variable amount of energy that is required to transport the same amount of goods as one MJ of fossil fuel.

[29] HFO = Heavy Fuel Oil, VLSFO = Very Low Sulphur Fuel Oil, MGO = Marine Gas Oil, LNG = Liquefied Natural Gas.
[30] $LH_2$ = Liquefied Hydrogen.
[31] FAME = Fatty Acid Methyl Esters, HVO = Hydrotreated Vegetable Oil.
[32] As a reminder, one ton of oil equivalent corresponds to nearly 42,000 megajoules.

**Well-to-Wake footprint of different alternative fuels for the maritime sector by 2030** ($gCO_2e$/ MJ fossil equivalent)




*Notes: (1) VLSFO = Very Low Sulfur Fuel Oil | (2) The term carbon footprint means that emissions are accounted for over the whole life cycle. | (3) The MJ fossil equivalent is the energy required to transport the same amount of cargo as 1 MJ of fossil fuel, whereas different fuels allow different carrying capacities and may require a pilot fuel. | (4) Hydrogen is considered "low-carbon" in the sense of the European Taxonomy (threshold of 3 $kgCO_2e$ / $kgH_2$). | (5) The $CO_2$ for the manufacture of e-methanol and e-LNG is considered as being captured directly from the air (Direct Air Capture). The carbon content of the electricity used for DAC is the same as for the production of low-carbon $H_2$. | (6) The footprint of LNG (Liquefied Natural Gas) presented here takes into account methane leakage throughout its value chain.*
*Sources: Carbone 4, based on JEC, Globiom, RED II, ICCT, SEALNG x SGMF, T&E, IEA*

In addition, we consider a **specificity for the use of gas** (fossil, BioNGL or syngas) as a marine fuel: **the effect of leakage which has a significant impact on its footprint**. As a matter of fact, methane (the main component of the gaseous fuels studied) released directly into the atmosphere has a global warming potential 100 years from now that is nearly 30 times greater than that of $CO_2$. These leaks occur throughout the life cycle of this fuel. First, **upstream of combustion, some methane escapes into the atmosphere during extraction and transportation by pipeline**. Then**, during combustion, the latter is not complete and part of the gas that is not burned escapes again into the atmosphere: these leaks correspond to the phenomenon of "*methane slip*"**. The amount of these leaks depends on many factors, such as the shape and size of the combustion chamber or the "tank load". The methane slip reduction is a concern for engine manufacturers, who expect a reduction in these leaks of up to 90%, depending on the engine, by 2030, which would result in a value of 0.8% of leaks (as a proportion of energy), the value retained in this report.

This initial carbon footprint analysis allows us to **rule out certain alternative fuels that are too carbon intensive:**

- **Fossil fuels** (VLSFO, MGO, HVO and LNG), not shown on the graph, are not low-carbon alternative fuels;
- **Blue ammonia**, which is produced from hydrogen obtained from the steam reforming of natural gas with a carbon capture and storage system, is not a very decarbonizing fuel because of its high pilot fuel requirement and low gravimetric energy density. In addition, its high toxicity and the creation of nitrogen dioxide during its combustion are major issues that are still being researched by engine manufacturers;

- **First generation** (1G) **bioenergy**[33] leads to land use change, including deforestation directly or indirectly. This generates significant emissions and thus makes it an unsustainable solution.

On the other hand, **some alternative fuels appear relevant from a carbon point of view**. This is the case of **second generation** (2G) **bioenergy**[34] and **synthetic fuels provided they are produced with low-carbon hydrogen**: e-LNG, e-ammonia, e-methanol and $LH_2$.

**As far as liquefied hydrogen is concerned**, **a major technical constraint remains: it is highly explosive**, which leads to safety constraints. **Moreover, no shipowner has yet succeeded in keeping $LH_2$ in a cargo tank for more than a fortnight before the** *boil-off* phenomenon (the liquefied hydrogen becomes gaseous again as it heats up) becomes uncontrollable, while a ship making transatlantic or transpacific voyages typically spends about 25 days at sea.

For **e-ammonia produced from low-carbon hydrogen, strong safety constraints remain regarding the toxicity of this gas** for humans and the environment. In addition, the potential risks of emissions of nitrous oxide (high global warming potential) and its lower decarbonizing potential than other e-fuels have led us to exclude it from the range of alternative fuels for decarbonizing the maritime sector in the medium term.

**Thus, it appears that 2nd generation bioenergy is the best placed for the sector**: this is true both **in terms of carbon footprint** as shown above, but **also in terms of costs**, according to (T&E, 2020). **However, as their deposits are limited, they must be complemented by e-fuels**. Among the e-fuels, **e-LNG and e-methanol are options that, even if more expensive, are successful**. Moreover, they can be deployed now: e-LNG can be used in an LNG engine (in this case, its reduction potential is lower than the one presented in the conclusion, which uses VLSFO as a reference) and methanol is a liquid fuel that is already known to the sector and can be used for existing vessels after *retrofitting*, a renovation operation that consists of changing the engine of a vessel.

### *The place of hydrogen in the future of the maritime sector*

To determine future hydrogen demand for the marine sector, **we assessed the share of e-fuels and bioenergy needed to achieve the sector's climate goals**. We do not consider liquefied hydrogen for the reasons explained above.

2G bioenergy seems to be the most relevant option with respect to the criteria studied above and allows decarbonizing the existing fleet because it is compatible with current engines. However, bioenergy is by nature limited by biomass resources, which are both complex to estimate and subject to significant competition of uses, whether for energy or non-energy purposes. For example, since their availability for the maritime sector is limited[35], it will be necessary to use e-fuels- as well. Depending on how much electrification of the road sector occurs, the volumes of 2G bioenergy available for the maritime sector may change significantly. In our study, we

[33] First generation bioenergy is a biofuel produced from crops traditionally used for food. More specifically, it is the reserve organs of oil plants or sugar plants that are used to produce biodiesel or bioethanol.
[34] Second-generation bioenergy, also called "advanced", is the successor of the current bioenergy (called first-generation) and is expected to solve the problem of competition with food production. They use only the non-edible parts of plants and biomass waste (e.g. agricultural waste or used cooking oil).
[35] Both because of the availability of waste biomass but also because of the competition with different segments of mobility such as road or air.

estimated the share of 2G bioliquids for the maritime sector in the range of 15% to 20% of the sector's energy needs in 2030[36].

**For the penetration of e-fuels in the sector, we have reasoned on the basis of their possible deployment dynamics**: some e-fuels require *ad hoc* engines, while others that are already compatible with current engines will be able to play the same role as biofuels to decarbonize the existing fleet. This is the case for e-LNG, which can be used directly by LNG engines. E-methanol, however, will require *retrofitting of* vessels to be used. However, for economic reasons, it is likely that the most recent vessels will benefit from these *retrofits as* a priority, i.e. nearly 5% of the fleet by 2030[37]. Finally, e-ammoniac would require adapted ship designs, so it would only be possible for new ship orders.

Considering these dynamic constraints and the improved efficiency of new engines, **e-fuels could constitute about ten to twenty percent of the fleet's fuel and would require volumes of about 10 to 20 MtH$_2$ depending on the availability of 2G bioenergy considered**. The amount of synthetic fuels to be mobilized is very sensitive to the availability of bioliquids for maritime use. On the other hand, hydrogen consumption is not very dependent on the choice of e-fuel which is favored in the scenarios. Thus, e-fuels have a similar hydrogen requirement for their production[38].

## Aviation

*The aviation sector today: carbon footprint and commitments*

Reasoning on combustion emissions, the aviation sector currently emits 3 to 4% of energy-related $CO_2$ emissions in the world (IEA, 2021). But let's remember that the impact of aviation on the climate is not limited to $CO_2$ emissions from jet fuel combustion. If we add the upstream fuel and the warming effect of condensation trails, air transport contributes more like 4% to global warming emissions (Klöwer, et al., 2021). And the upward trend remains very strong despite the health crisis: after a growth of 4% per year between 2010 and 2018, the actors of the sector foresee a post-covid growth of about 3.6% per year (ICAO, 2021).

The States, through the ICAO (International Civil Aviation Organization)[39], have committed themselves to "neutral growth" in the sector, i.e. to a growth in activity as currently anticipated with the implementation of emission reduction levers so as not to emit more than currently. More recently, the member airlines of the International Air Transport Association (IATA)[40] have set a more ambitious goal: to be carbon neutral in their direct emissions by 2050.

These commitments in terms of "neutrality" or "neutral growth" of the sector are open to criticism[41]. For the purposes of the study, we need to reason about the actual reduction in emissions from the sector. Given the level of carbon offsets announced, IATA's commitment corresponds to the IEA's B2DS emissions target in 2050, i.e., about 340 Mt$CO_2$, compared to about 1,000 Mt$CO_2$ currently, for a doubling of passenger traffic.

---

[36] These estimates are based on the 2G diesel and gasoline volumes considered in the IEA Net Zero scenario (IEA, 2021).
[37] That is, vessels 10 years old or less in 2030. Source: interviews with industry experts.
[38] Reduced to the functional unit, here the MJ fossil equivalent.
[39] The ICAO is a branch of the United Nations which represents the various aeronautical authorities of the member countries of the UN.
[40] IATA is an international trade organization of air transport companies, and a lobby. Most scheduled airlines are represented.
[41] See for example the articles of Carbone 4 on this subject , such as this one: " Ne dites plus "compensation": De la compensation à la contribution ".
https://www.carbone4.com/neditespluscompensation-de-compensation-a-contribution.

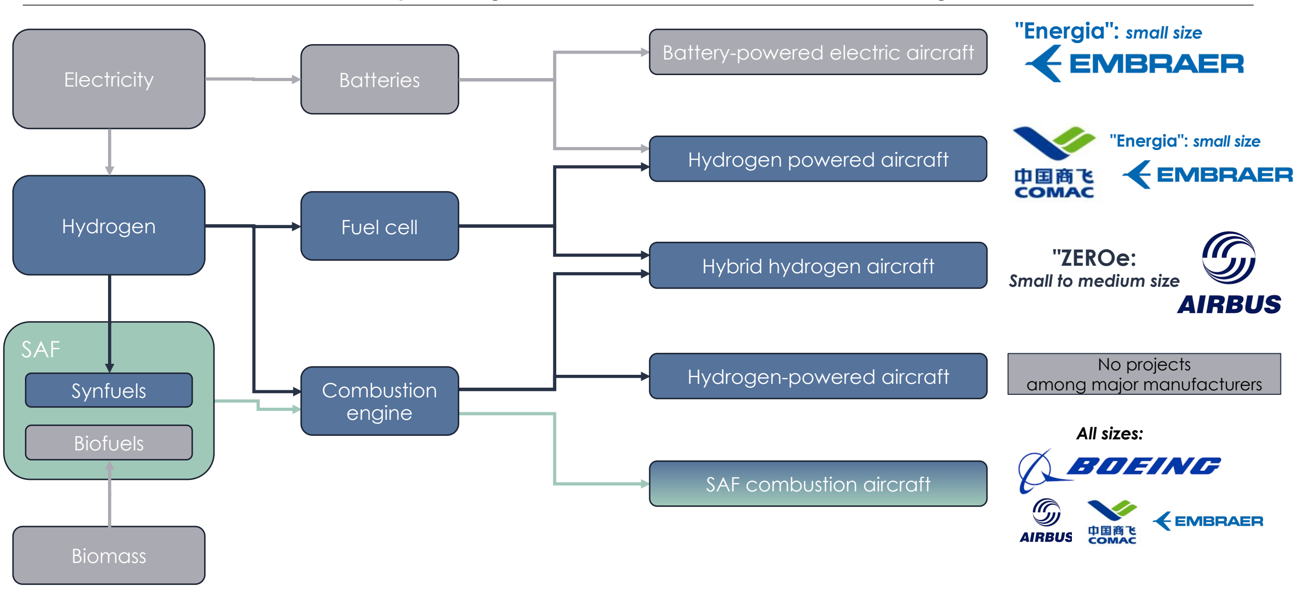
## *The aviation sector tomorrow: what are the levers for reducing emissions?*

**Long-haul and medium-haul commercial flights together account for 80% of the sector's emissions**. To date, there are no clear prospects for the use of hydrogen on this type of flight, despite a strong interest, at least in France, in hydrogen-powered aircraft.

Using hydrogen in an aircraft could be done directly (combustion or fuel cell) or, as in the maritime sector, as an intermediate reagent to produce synthetic fuels, or synfuels. These synfuels are a form of SAF[42], alongside fuels from biomass.

We have analyzed the technology roadmaps of the world's major aircraft manufacturers. Most manufacturers tend to be in favor of SAF. Some of them, and Airbus in particular, hope to market hydrogen powered aircraft from 2035 onwards, but only for small short-haul aircraft; they are considering the use of hydrogen for medium-haul aircraft in the longer term (Frost, 2021). In the short-haul- sector, the development of battery-powered aircraft is also underway and would therefore be in competition with hydrogen.

**Possible uses of electricity and biomass in the aviation sector and the positioning of manufacturers on the associated technologies**




## *The place of hydrogen in the future of the aviation sector*

The direct use of hydrogen in the aviation sector has of course important advantages such as the **reduction of $CO_2$[43], NOx[44] and contrail effects[45].** Also, **the direct use of hydrogen allows for a more efficient use of available energy** because synthetic SAF (e-kerosene) requires an additional hydrogen transformation step and thus additional energy consumption[46]. This aspect gives

[42] SAF = Sustainable Alternative Fuels or Sustainable Aviation Fuels.
[43] There is literally no carbon in the direct emissions, and little in the carbon footprint as long as the $H_2$ is itself low carbon.
[44] And even the elimination of NOx for fuel cells, for which there is no combustion.
[45] The expected reductions are in the order of 30% to 50% for hydrogen combustion and 60% to 80% for fuel cells (McKinsey, 2020).
[46] Although hydrogen aircraft will probably consume at least 10% more energy than conventional aircraft, Fischer-Tropsch e-kerosene production requires about 40% more electricity than LH production$_2$.

hydrogen an additional advantage over synthetic FAS: **hydrogen allows for a greater reduction in emissions as well as a more efficient use of the limited low-carbon electricity supply**. In addition, **the solution would be less expensive than synthetic SAF for short to medium haul** (McKinsey, 2020) (ICCT, 2022).

However, many substantial factors are not in favor of the direct use of hydrogen for aviation:

- **The constraints of volumetric energy density and mass density penalize hydrogen**, both for the fuel itself (for energy density), but also indirectly through the cooling and pressurization system it requires (for mass density). This would lead to a 40 to 50% increase in long-haul costs due to a higher energy demand generated by the effect of the additional mass (McKinsey, 2020).
- **Few models** are proposed by manufacturers, only for short and medium-haul aircraft, and not before 2035.
- **The refueling infrastructure** dedicated to hydrogen aircraft must necessarily be developed in a uniform and coordinated manner on a global scale, as the aircraft must be able to be used everywhere by airlines.
- **Safety issues** are strongly anchored in the culture of the aviation sector. Hydrogen presents risks due to its explosive nature, which implies complexity for the engine supply circuits to compensate for hydrogen evaporation (Wachenheim, 2021).
- **Its cost is higher than** biofuels, and e-fuels on long-haul routes (McKinsey, 2020).

Thus, it is **very unlikely that hydrogen, used directly as fuel in aircraft, will acquire a significant place in the aviation sector in the long term**, and **it is impossible to see it emerge by 2035 for medium and long-haul aircraft** because the first aircraft will not yet be commercialized. By 2050, hydrogen can be used in a significant way indirectly: as the biofuel supply is limited, and as several sectors are competing for access to it, it is likely that they will not be sufficient on their own, unless air traffic is reduced accordingly. Therefore, the use of hydrogen may be necessary for the production of e-kerosene. As for the maritime sector, the quantities to be mobilized will be very sensitive to the availability of biomass and it is therefore difficult to anticipate the volumes of demand.

### *Hydrogen volumes by 2035*

Given the hydrogen aircraft development roadmaps, the **industry's hydrogen consumption in 2035 will be almost exclusively dedicated to SAF production**. IATA sets a target threshold of 17% SAF to be achieved over this time horizon. It is very likely that this threshold will be **reached mainly with biofuels** and that the volumes of hydrogen called by the sector will be almost zero. However, **the European Union has a draft regulation with minimum incorporation rates of Renewable Fuel of Non-Biological Origin (RFNBO) of 5% in 2035. If this minimum rate were generalized worldwide, the volumes of hydrogen called for would be in the order of 5 $MtH_2$ per year in 2035**. The same calculation principle, applied in 2030, would give less than 1 $MtH_2$ in 2030 if the European minimum rate of 0.7% of RFNBO were generalized to the world.

*Hydrogen volumes by 2050*

According to IATA, the SAF incorporation threshold should reach 65% in 2050. The IEA also estimates that the demand for biofuels for the sector could cover 40% of the sector's fuel needs (IEA, 2021). In this scenario, e-kerosene should cover 25% of the sector's needs. The draft European regulation is more ambitious in terms of RFNBO incorporation and sets a threshold of 28% in 2050. In the scenarios presented here[47], the **hydrogen volumes required for SAF production are 40 to 45 $MtH_2$ per year.**

**By 2050, hydrogen-powered aircraft will have begun to penetrate the short and medium-haul sector**. On short-haul routes, they will compete with battery-powered aircraft, which seem realistic for this segment. The split between these two technologies will depend on the progress made by manufacturers between now and then. Considering the speed of fleet renewal and the dates of first commercialization of these new engines, **hydrogen aircraft could represent a little more than 10% of the traffic[48] in 2050**, with a variation of the order of one percent depending on the penetration of battery aircraft. The **corresponding hydrogen volumes are 20 to 30 $MtH_2$ per year**. These volumes are sensitive to the penetration assumptions of competing solutions, such as batteries, but very little to the engine technology, direct combustion or fuel cell.

Thus, **for these two uses combined, hydrogen demand could reach 60 to 70 $MtH_2$ per year by 2050**.

## Trucks

*The road freight sector today: carbon footprint and areas for reduction*

Today, although it is responsible for only 18% of the volume of goods transported in ton-kilometers, **road freight accounts for 65% of the $CO_2$ emissions of the freight sector**[49], i.e. **more than 2 billion tons of $CO_2e$ each year**[50]. This is due to the almost exclusive use of oil-based fuels, primarily diesel. This is the most carbon-intensive mode of transport per ton transported and per kilometer after air transport, although the latter remains very anecdotal in terms of freight transport activity (ton-kilometers).

In order to reduce road freight emissions, there are **at least two levers that can be activated before focusing on the trucks themselves**. The first and most effective is to **reduce the volumes transported and the distances covered**, which can be achieved by reducing the consumption of goods but also by increasing load factors or by bringing the production and consumption areas of these goods closer together. The second is to **shift some of this freight to other, less carbon-intensive modes of transport,** such as rail, maritime and waterway.

Then there are **levers that affect unit emissions from trucks**, which are addressed by a number of measures and commitments, starting with European regulations. The latter requires a 15% reduction in emissions from new trucks by 2025 and a 30% reduction by 2030 compared to 2019-2020. **While improvements in engine efficiency are welcome, they cannot sufficiently reduce truck emissions, and it is primarily a shift in energy carrier that is needed.**

[47] The two scenarios are either the IEA projections or the generalization of the European minimum rates to the entire sector.
[48] In passenger-kilometers.
[49] Data for the year 2019. Source: OECD.
[50] Ibid. The $CO_2$ emissions of freight are 3.2 billion tons of $CO_2$.

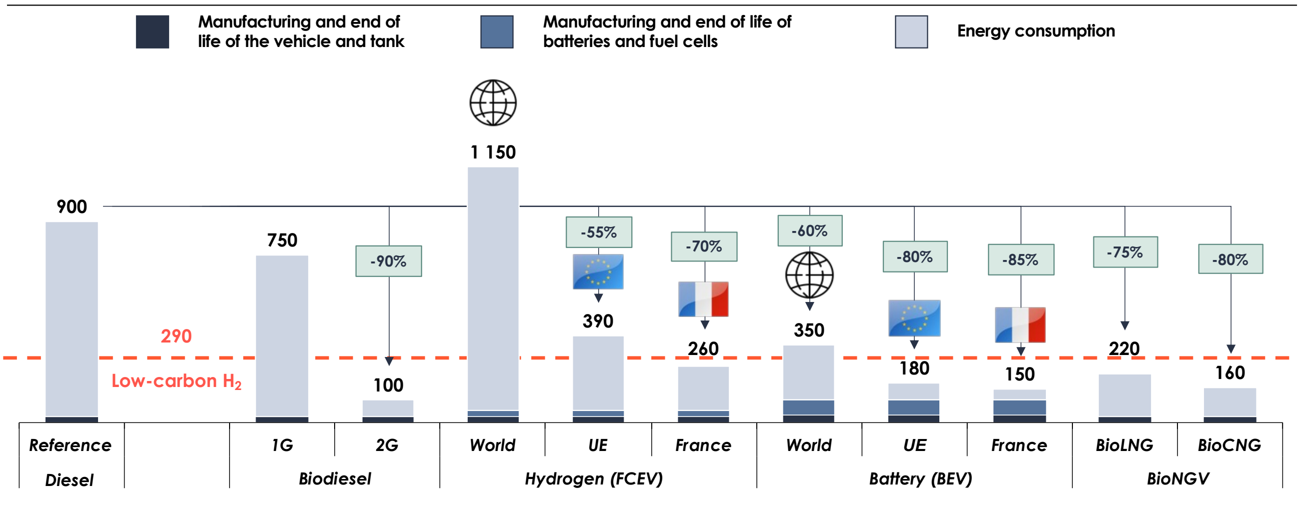
*The road freight sector of tomorrow: which energy carriers to choose?*

**Four alternatives to diesel fuel were studied** in terms of their ability to reduce unit emissions from trucks:

- Thermal trucks running on **1st or 2nd generation biofuels** (resp. 1G or 2G);
- Thermal trucks running on **biomethane (BioNGV),** whether compressed (BioCNG) or liquefied (BioLNG);
- **Electric trucks with batteries (BEV)**, recharged with electricity;
- **Electric trucks with fuel cells (FCEV)**, recharged with hydrogen[51].

The comparative analysis of these options in terms of carbon allows us to assess their respective capacity to decarbonize a reference situation defined by the diesel truck. The following figure is based on semi-trailer-trucks, but the lessons can be transposed to smaller trucks.

**Carbon footprint of a semi-trailer truck purchased in 2030 by engine and geography** ($gCO_2e$ / km)




*Assumptions: 1,200,000 km driven over the truck's lifetime; battery capacity of 1,000 kWh for electric trucks; calculations take into account a gradual decarbonization of the electric mix concerned, according to an IEA scenario (WEO 2020 SDS, a medium-term scenario aligned with the Paris Agreement) and the French PPE.*
*Acronyms: BEV for Battery Electric Vehicle; FCEV for Fuel Cell Electric Vehicle; CNG for Compressed Natural Gas; LNG for Liquefied Natural Gas.*
*Notes: (1) The term carbon footprint means that emissions are accounted for over the whole life cycle. | (2) The low-carbon $H_2$ threshold shown is the maximum emissions of an FCEV semi-trailer truck for the $H_2$ it consumes to be considered low-carbon according to the European Taxonomy (3 $kgCO_2e$ / $kgH_2$).*
*Sources: Carbone 4 analysis*

For thermal engines, **1G biofuels are far from being decarbonizing enough and are not a credible alternative to diesel. 2G biofuels and BioNGV**, on the other hand, are both **very decarbonizing** candidates **for the sector**.

**The carbon footprint of BEVs and FCEVs depends very strongly on the carbon content of the electricity** used to power the trucks, either directly for BEVs or indirectly for FCEVs. In practice, this

[51] The fuel cell is used to perform the reverse chemical reaction of water electrolysis: hydrogen from a storage device on the truck and oxygen from the ambient air react to form water while releasing energy in the form of electricity. Hydrogen-fueled thermal trucks have not been studied because the technology is less mature than FCEVs.

leads to **highly variable emissions depending on geography, as long as** the electricity considered is that of the network and the production mix that powers it. In a relatively sustained decarbonization perspective, an electric truck purchased in 2030[52], whether it runs on electricity or hydrogen, could be considered sufficiently low-carbon depending on the context, with emissions that remain higher for FCEV.

With low-carbon hydrogen at the European Taxonomy threshold (3 $kgCO_2e$ / $kgH_2$) and in a scenario of evolution of the carbon content of electricity aligned with the decarbonization of the economy, **an FCEV in France could be considered as running on low-carbon hydrogen, but this is not valid on average in the EU and even less in the world**. In fact, the world average carbon intensity of electricity at these time horizons would be so high that the hydrogen truck would be more carbon intensive than the diesel truck, with a **threshold value around 150 $gCO_2e$ / kWh of electricity to equal the emissions of the diesel truck. Conversely, if the FCEV were to be as decarbonizing as the BEV, very low levels of carbon intensity for electricity would have to be achieved, on the order of 10 $gCO_2e$ / kWh**. Below this level of electricity carbon intensity, the excess emissions for battery manufacturing over the fuel cell outweigh the effect of the higher in-use emissions for FCEV.

### *What role for hydrogen in the future for short and medium distance road freight?*

**In order to address the plurality of real-life situations in a more detailed way, the study divided road freight into two segments, which present specific challenges: short and medium distance freight on the one hand, and long-distance freight on the other**. For each segment, a reflection based on both quantitative and qualitative elements allowed us to take a position on the role that hydrogen could play in a low-carbon transition.

**In this study, short and medium distance is defined as journeys of less than 500 km per day**[53]. It therefore concerns both urban and regional freight, and mainly involves vans and light trucks.

**The growing number of regulations concerning air quality in urban areas favors electric engines (BEV or FCEV)** to the detriment of internal combustion engines, which are responsible for emissions of fine particles[54] and NOx, due to the very nature of the operation of the combustion engine. NOx molecules are formed with the nitrogen present in the air entering the combustion engine, because it is not possible to have controlled combustion with pure oxygen.

**Bioenergy is also limited by biomass resources**, which are both complex to estimate and subject to significant competition for energy and non-energy uses. If biomass resources were to be allocated to the road sector, it would seem more appropriate to reserve them for long-distance trips, which are more difficult to electrify.

**In light of these elements, the battery electric truck seems to be the option to be prioritized for decarbonizing the short and medium distance road freight segment**. It is already mature enough to meet the demand for the type of distances covered, whereas the hydrogen truck is less

[52] In order to take into account the lifetime of the vehicles, the emissions are calculated considering the average carbon content of electricity over the decade 2030.
[53] In 2019, it accounted for 61% of ton-kilometers and 64% of vehicle-kilometers in the EU28. Source: Eurostat.
[54] However, it is important to remember that the fine particles emitted by a truck are not only caused by combustion, but also by wear and tear on the roads, tires and brakes.

advanced industrially, more carbon intensive and probably more expensive than the battery truck[55].

*What role for hydrogen in the future for long-distance road freight?*

**In this study, long distance is defined as journeys of more than 500 km per day**[56]. It concerns national and even international freight.

**Alternative thermal engines based on biomass are already mature and have characteristics very similar to diesel trucks** in terms of transportable capacity, range, recharging time and driving characteristics. However, **even if the biomass resources are focused primarily on long-distance transport, they remain limited** and will probably be insufficient to cover the needs of this segment.

The autonomy and the transportable capacity of the battery truck are directly linked to the energy capacity of its battery. **The usual size batteries are far from allowing a similar autonomy to the diesel truck, in addition to requiring high recharging times**. Increasing the size of the battery would help to overcome the need for range; however, the truck battery is the most expensive component, the one that puts the most strain on manufacturing materials, and a major contributor to the carbon footprint.

However, **in a context of rationalizing the allocation of low-carbon electricity, a BEV is 2 to 3 times more efficient than an FCEV over the whole value chain from electricity production to transmission of driving energy to the axles**. This difference is due to the energy losses that occur at each of the transformations, first for the transformation of electricity into hydrogen by electrolysis and then back into electricity via the fuel cell. In addition to this increased electricity consumption, which makes the FCEV more expensive to operate than the BEV, **the hydrogen truck is expected to remain more expensive to manufacture in the near future**[57].

**In addition, constraints on the range and recharge time of battery-powered trucks can be partially overcome in two ways**. First, regulations can impose, as is the case in Europe, **regular breaks for truck drivers**[58], which can be used to recharge the batteries. Long breaks allow for slow, full recharging, while fast charging stations allow for recharging during short breaks. A high frequency of breaks also allows trucks with a short range to cover long distances thanks to regular recharging. The second lever concerns **the organization of logistics flows**. Changing the way we think about journeys, for example with **low-carbon convoys between terminals**, which are easier to equip with fast charging stations, or by relying on **dynamic charging infrastructure such as electric highways**[59], can significantly reduce the size of electric truck batteries, although some technological options still need to mature.

**Finally, the timing of deployment works against the hydrogen truck compared to its battery competitor**. On the one hand, manufacturers are more advanced on the maturity of BEVs, while their announcements do not call for significant commercialization of FCEVs in the near future, but

[55] Full cost of ownership reasoning. Sources: T&E, 2020; ICCT, 2021.
[56] In 2019, it accounted for 39% of ton-kilometers and 36% of vehicle-kilometers in the EU28. Source: Eurostat.
[57] By 2030, an FCEV could be twice as expensive as a BEV to purchase. Source: ICCT, 2022.
[58] In the EU, a break of at least 45 minutes is required every 4.5 hours of driving. In addition, the daily driving time must not exceed 9 hours (about 800 km at 90 km/h) and a daily break of 11 hours is required. Source: MTE.
[59] The electric highway allows trucks to be recharged dynamically, using catenaries, rails or induction. Trials have already taken place in Europe (Sweden, Italy, Germany) and the United States (California). In France, at least one concessionaire is planning to test a form of electric highway, with the aim of having electric trucks take over from diesel trucks on electrified highway sections.

rather from the second half of the decade[60]. It is likely that by that time, battery technology will have continued to evolve and will be even more mature than today, including technically. **The tightening of regulations on new trucks regarding emissions limits is also pushing manufacturers to market low-emission vehicles in the short term**, which hydrogen technology does not yet allow. This may lead manufacturers to push a battery truck strategy. Finally, like battery-powered trucks, hydrogen trucks require *ad hoc* infrastructure deployments for hydrogen charging and distribution, which is not the case for biofuel trucks and less significant for BioNGV trucks. **Developing both hydrogen and battery technologies would require the mobilization of a double industrial apparatus and heavy investments**. It may seem difficult to envisage a parallel deployment of these two distinct networks; however, **electric infrastructure are the ones likely to develop first**, driven by the development of battery-powered trucks in regional logistics and in synergy with the needs for long-distance trips by light vehicles.

Thus, in terms of the dynamics of BEV and FCEV deployment by mid-century, **it is not impossible that the story will be determined by the first step to be taken** (the concept of "path dependence" in economics): the development of BEVs in the short to medium term requires infrastructure and organizational changes in supply chains (to overcome the decrease in range compared to current diesel trucks). **Once the infrastructure for battery-powered trucks has been deployed, and the organizational changes have been implemented, it is unlikely that a new movement will be set in motion for a massive deployment of FCEVs**, as this would lead to a reduction in the amortization of the infrastructure for BEVs on the one hand, and to a re-design of the logistics organization on the other hand. Although this would probably not have a major impact on the overall demand for hydrogen, it is not impossible that the hydrogen truck will develop more particularly in specific segments, for example certain captive fleets.

In view of the previous elements, **the hydrogen truck can play a role in the decarbonization of long-distance road freight in addition to other low-carbon technological options**. **However, the technical and industrial constraints linked to its deployment do not allow us to foresee a strong penetration of this alternative by 2030**, so if it is to develop, it will be beyond this timeframe.

*Hydrogen volumes for 2030 and 2050*

Assessing the capacity of hydrogen to penetrate the road freight sector is a complex exercise, which several studies have attempted without arriving at a convergent vision, and Carbone 4 does not claim to provide a definitive assessment. However, we have estimated hydrogen volumes for the 2030 and 2050 horizons.

If the hydrogen truck manages to represent 10% of long-distance sales by the end of the decade, which already seems relatively ambitious in view of the manufacturers' announcements, it will probably not be able to exceed **5% of the trucks in circulation in 2030,** given the lifespan of the vehicles and therefore the inertia of the fleet replacement. **By 2050, it seems perilous to choose between the four technological options** (biofuels, BioNGV, BEV and FCEV): a simplistic position is to **give each of them, including the hydrogen truck, a 25% share of the trucks**. According to the recent IEA *Net Zero by 2050* scenario (IEA, 2021)[61], global road transport volumes (all distances) are expected to increase from 27 trillion ton-kilometers in 2019 to 38 trillion ton-kilometers in 2030 and

---

[60] Source: Recharge, 2022, according to the Fraunhofer Institute.

[61] This scenario, which is the result of convergence between the WEO and ETP scenario families, proposes a pathway for achieving global carbon neutrality by 2050.

60 trillion ton-kilometers in 2050. Under these assumptions and some additional ones[62], **hydrogen demand for long-haul road freight would be 4 $MtH_2$ in 2030 and would reach 25 $MtH_2$ in 2050**.

## Railway

**The rail sector is the most electrified mobility sector already, but there are still diesel engines in operation worldwide**: 25% of passenger traffic and 50% of freight in 2017 (IEA, 2019). Hydrogen coupled with a fuel cell could be a solution for replacing these trains. This is the objective announced by several roadmaps of the sector or governments, especially in Europe[63].

**However, the interest of hydrogen in the sector seems to be rather limited,** considering both the low volumes that can be addressed (only 2% of the energy demand of the transport sector (IEA, 2019)), but also its competition with electrification, whether it is based on continuous charging (via catenaries) or discontinuous charging and the use of batteries in trains. In fact, **for new or short, high-traffic sections, hydrogen is less economically relevant than direct electrification of tracks**[64]. Hydrogen is **also more expensive than batteries because it entails various additional costs**: for fuel cells (for which the rail sector is currently a niche market, and which are therefore not optimized for the sector's specific uses) and for the adaptation of infrastructure (technology centers and stations).

**However, its greater autonomy than batteries and the difficulty that direct electrification can present for certain types of roads** (for example in the mountains with frequent structures such as tunnels and bridges) **make the hydrogen train relevant for regional lines with less traffic, which are little or not electrified and which have greater distances to cover.**

For our study, **we have chosen to refer to the prospective analyses of pro-hydrogen actors in order to retain a majorant of** the volumes of hydrogen called by the sector by 2030. We have chosen the value of **3 $MtH_2$ per year**, proposed by the Hydrogen Council in its report *Hydrogen for Net-Zero* (McKinsey for Hydrogen Council, 2021).

[62] Assumptions: Long-distance weight derived from European statistics 2019 and considered constant over time | Weight transported by truck derived from European statistics 2019 with an increase of 5% by 2030 and 15% by 2050 | Kilometric consumption of 7.8 $kgH_2$ / 100km in 2030 and 7 $kgH_2$ / 100km in 2050.

[63] Germany, France, Italy and the United Kingdom have committed to orders with Alstom for delivery before 2025, and successful trials by the manufacturer have taken place in Austria, Sweden and the Netherlands.

[64] The cost structure of direct track electrification is dominated by CAPEX, while that of locomotive hydrogenization is dominated by OPEX. For an "intensive" use, the electrification of the tracks becomes less expensive.

# What are the prospects for hydrogen in the energy sector?

## Refining

*The sector today: hydrogen footprint and consumption*

**Refining is the sector that consumes the most hydrogen in the world** with 38 $MtH_2$ consumed in 2018, representing **33% of global demand**. On average, 35% of the hydrogen consumed by the sector is co-produced on site by steam crackers. **Dedicated hydrogen production is responsible for about 20% of the sector's greenhouse gas emissions** (IEA, 2019).

Unlike other segments of the energy sector, **hydrogen is also used by refineries as a reagent** for three distinct purposes:

- **Hydrocracking**, which consists in **breaking a complex organic molecule into smaller elements** by hydrogenating them. This is mainly used in the production of diesel, heavy fuel oils and kerosene. This process consumes nearly 300 $m^3$ of hydrogen per $m^3$ of fuel and represents more than 80% of hydrogen consumption by refineries in 2017;
- **Hydrodesulfurization**, which is a process used in oil refining to **remove sulfur from** medium fractions such as heavy diesel, gasoline or fuel oil. The hydrogen consumption of the process depends on the sulfur content of the fuel and represents about 17% of the hydrogen consumed by refineries in 2017;
- **Hydrodeoxygenation**, which consists of **the elimination of oxygen** in certain components. This process **concerns biofuels**, consumes about 50 to 60 $m^3$ of hydrogen per $m^3$ of fuel and represents about 1% of the hydrogen consumed by refineries in 2017.

*Tomorrow's refineries: what changes in hydrogen demand?*

**Several factors are determining the demand** for hydrogen by refineries: **the evolution of regulations on the sulfur content** of petroleum products, **the evolution of the sulfur content of crude oil** entering refineries and finally **the evolution of the volumes and mix of fuel demand**.

First of all, **regulations tend to reduce the acceptable sulfur content of petroleum products**. For example, as of January 1, 2020, the International Maritime Organization's new regulations require that the sulfur content in marine fuels be reduced from 3.5% to 0.5%. The higher the amount of sulfur to be removed, the more hydrogen is consumed in the desulfurization process. Thus, the tightening of regulations is a factor that is increasing the demand for hydrogen in the sector.

In addition, **changes in the quality of crude oil entering refineries influence its sulfur content**. Heavy crude oil has four times the sulfur content of light crude oil and requires twice as much hydrogen. The current trend is to increase the share of heavy crude oil entering refineries, and this factor tends to increase hydrogen demand in the sector. However, in a scenario of compliance with the Paris Agreement, the consumption of petroleum products is expected to slow down sharply by 2030, which will limit the evolution of the average density of crude oil in 2030[65]. In 2017, the "heavy" / "light" proportion was about 50%/50%. In the scenario respecting the Paris Agreement, we consider an evolution of this proportion towards 55%/45% in 2030.

Finally, and still assuming compliance with the Paris Agreement, **the demand for oil products should decrease by more than 20% by 2030 compared to 2017**, while **the share of biofuels should be multiplied by 3**. In particular, the consumption of gasoline and heavy fuel oil for electricity production should be divided by 1.5 and 3 respectively over this time horizon (IEA, 2014). As biofuel processing requires less hydrogen than other petroleum products and the total volume of refined products is decreasing, the evolution of fuel demand is a factor that tends to reduce hydrogen demand from refineries.

**When these three factors with antagonistic effects are taken into account, we arrive at a stable hydrogen consumption by refineries**, although the use of the molecule is distributed differently between the three processes detailed above. However, **in the longer term, the effect of the decline in oil products will lead to a reduction in hydrogen volumes of 58% between 2030 and 2050 in the IEA scenario** (IEA, 2014).

### *The place of hydrogen in the future of refineries*

Given the amount of hydrogen produced in a dedicated way for refineries (about 65%), the volumes that can be addressed by low-carbon hydrogen in 2030 are significant: **about 25 $MtH_2$ per year**. However, its **decarbonizing potential is quite low on the whole emissions of the refining sector, about 15%**: the production of hydrogen used by refineries, more than 90% by steam methane reforming, represents only about 20% of the emissions of the sector (IEA, 2019). However, **the decarbonization of the hydrogen consumed is one of the only ways to reduce the sector's emissions, along with carbon capture and sequestration**. **The use of low-carbon hydrogen could therefore be done in a transitory way, by accompanying the sector's decline**.

## Mixed consumption in gas networks

### *Gas networks today: consumption and emissions*

**Today, gas, almost exclusively fossil gas called natural gas and composed mainly of methane, is mainly used to produce electricity and heat by combustion. It represents a quarter of the world's primary energy consumption and about 15% of greenhouse gas emissions**. While it is consumed in a diffuse way, its extraction is relatively centralized, which induces the need to transfer it from the production basins to the consumption basins. To do so, the historical solution consists of transferring the gas through pipelines, to form the transport and distribution networks (respectively high and low pressure). An alternative option, boosted by the war in Ukraine, concerning about 10 to 20% of the gas today, consists in liquefying the gas and transporting it by ship over long distances - this is LNG.

[65] Demand is primarily produced from so-called "conventional" sources (light crude oil) which are easier to exploit. In the context of a contained increase in hydrocarbon consumption, the share of unconventional crude oil will be lower than in a scenario where hydrocarbon demand grows strongly, hence a slight increase in the share of these sources in the mix of crude oil entering refineries in our scenario.

*Tomorrow's gas networks: decarbonization axes*

**In order to reduce the consumption of fossil fuels, to free ourselves from one of the main sources of global emissions but also from a major cause of physical and geopolitical tensions as the war in Ukraine tragically reminds us, several levers must be mobilized**. First, **reducing energy consumption through sufficiency and efficiency actions**, for example related to the performance of buildings and industrial and non-industrial equipment. Second, **changing the energy carrier, for example by electrifying certain uses or switching to biomass**. Finally, the **replacement of fossil gas by other fuels within the networks, such as renewable methane or low-carbon hydrogen**.

*Hydrogen to decarbonize gas networks*

Like methane ($CH_4$), hydrogen ($H_2$) releases energy when burned. These two gases can therefore meet similar needs to produce heat and electricity, which is why studies are being carried out on the **possibility of injecting hydrogen into gas networks to replace at least part of the fossil gas that passes through them**.

In fact, **this is not a new development**: hydrogen was already in transit in gas networks in the past, like "town gas", a mixture of hydrogen, carbon monoxide and then natural gas, which supplied many French cities during the 19th and 20th centuries for uses such as public lighting or domestic cooking.

According to the European Taxonomy, the combustion of low-carbon hydrogen cannot exceed 90 $kgCO_2e$ / $MWh_{LHV}$, while the combustion emissions of natural gas amount to 227 $kgCO_2e$ / $MWh_{LHV}$ (ADEME, France). **The replacement of natural gas by low-carbon hydrogen leads to a 60% reduction in emissions, in addition to a reduction in fine particle emissions**[66].

*The limited potential of hydrogen to decarbonize gas networks*

**However, the consumption of hydrogen in gas networks raises questions on a technical and economic level**. It is necessary to ensure that the network infrastructure and the consumer devices at the end of the chain can **manage a $H_2$ / $CH_4$ mixture**, which is not necessarily guaranteed at this time. **Feasibility studies, which are still underway, suggest that injection is possible, provided a certain number of criteria are met**. For example, in France, a consortium of gas operators concluded that most networks were already able to accommodate up to 6% hydrogen by volume without major modifications and that this penetration rate could realistically rise to 20% with reasonable investments in both infrastructure and equipment. **Beyond 20% hydrogen by volume, the transformations of the gas system to be implemented would be of a much greater magnitude**, in particular concerning the adaptation of residential, tertiary and industrial equipment (French Gas Operators, 2019). In light of these elements, it seems **very unlikely that hydrogen injection could exceed 20% in volume, at least by 2030**.

The volumetric energy density of hydrogen is three times lower than that of natural gas. Thus, **a 20% volume injection of hydrogen, which would represent a significant demand for hydrogen, would replace only 6% of the energy in the network**. At a decarbonizing potential of 60% per unit

[66] The combustion of pure hydrogen does not release harmful particles, because the molecule does not contain a carbon atom in its composition.

of energy, **this would lead to a reduction in network emissions of only 3.5%**. While the use of hydrogen in gas networks would reduce the carbon footprint of gas consumption, this option is **far from being able to meet the magnitude of the emissions reduction that is needed**.

In addition to the technical aspects, **the cost of this option seems very high**: on the production perimeter alone, the additional cost of hydrogen could be around 80 € / $MWh_{LHV}$ by 2030, for an emission reduction of about 140 $kgCO_2e$ / $MWh_{LHV}$, leading to **an abatement cost exceeding 550 € / $tCO_2e$ avoided**. A full cost approach, including in particular the transmission and distribution network as well as storage, would lead to an even higher abatement cost. However, these elements should be considered with caution in view of the recent evolution of natural gas prices: if their production cost were to remain at high levels, the abatement costs of hydrogen injection would be reduced.

**In view of the elements discussed, the production of hydrogen with the aim of injecting it into the gas networks does not seem to be the most efficient way to reduce the global emissions of our societies**. Subject to technical compliance, injection can however be used to temporarily and locally ensure an outlet for hydrogen production if the production facilities are structured before those of consumption.

Moreover, our assessment here focuses on the injection of hydrogen into the gas networks with the aim of consuming this hydrogen in a mixture with the gas. **This does not invalidate the interest that hydrogen injection could have for transport purposes**: in this case, the hydrogen would transit in the networks, but would leave the networks (by separation) once it arrives at its destination. However, to assess the relevance of this option, it is necessary **to pay attention to the scientific studies underway on the global warming potential of the hydrogen** released into the atmosphere, as gas networks always have leakage rates, even if they are low.

## Storage for the electric power system

### *Electricity storage today: definition and characteristics*

Electricity is a form of energy that cannot be stored as such[67], as it is by definition the movement of electrons. **When we talk about electricity storage, we are in fact talking about the transformation of electrical energy into a storable form and then its inverse transformation into electrical form at the appropriate moments**. However, the proper functioning of the electricity network requires that at any given time there is as much consumption as there is production of electricity: we speak of supply-demand balance. **To meet this challenge of supply-demand balance of the power system, there are several flexibilities that can be mobilized, including storage**, which allows energy to be recovered when production is in surplus and then released during a period when consumption is too high.

Existing storage technologies (deployed and deployable within a reasonable timeframe) are diverse in nature and have specific technical and economic characteristics and maturity levels. Thus, some aim to respond very quickly to a disturbance on the electrical network, while others have very high-power levels in order to compensate for significant gaps between supply and demand over a given period, and other storage modes offer significant energy capacities to be able to displace part of the consumption over a more or less long period of time. **No single technology can meet the multiple challenges of storage and a variety of options must be**

[67] However, direct electrical storage may exist for research applications, for example by means of superconductors.

**considered depending on the services expected**. The main means of storage now, both in terms of power and energy capacity, consists of raising water to store potential energy from gravity and then releasing it through a turbine to produce electricity. This is the PSH[68], capable of displacing electrical consumption over several days.

### *Tomorrow's electricity production: an increase in variable production*

**Electricity production is on the rise and will continue to develop for two major reasons**. First, to **provide access to electricity for all**, in line with Sustainable Development Goal 7, while 10% of the world's population does not have access to electricity (UN, 2021). Secondly, and this is the main driver of the increase to be expected, **the electrification of uses** is a major brick in all the low-carbon transition scenarios. However, electricity production is responsible for a quarter of the world's greenhouse gas emissions due to the overwhelming use of fossil fuels, and compliance with the Paris Agreement means moving away from these carbon-based energy sources (except in cases where carbon capture is deployed on fossil fuel power plants).

**Caught between a projected increase in electricity consumption and a projected decrease in fossil fuel based production, low-carbon electricity production will have to develop very strongly. Among the possible options, wind and photovoltaic energy**, which currently represent less than 10% of global production (EMBER, 2021), may be required to develop very strongly (IPCC, 2018). **These means of production, which are said to be variable because their operation varies according to weather conditions** (wind regime and sunshine), **do not make it possible to supply electricity in a manner that is as controllable as conventional means of production** (thermal power plants, hydroelectric dams, etc.).

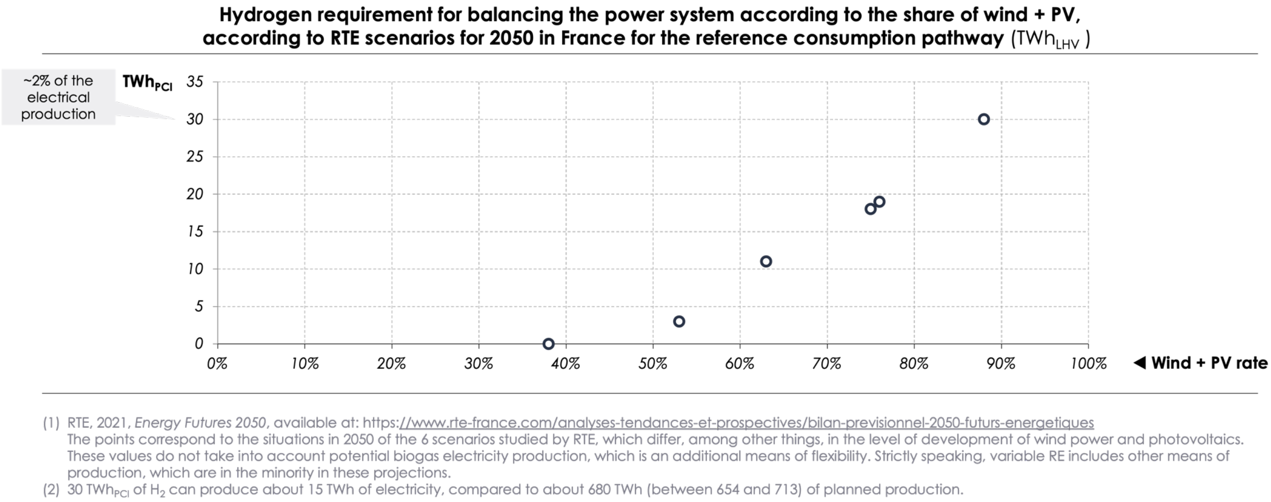
### *Tomorrow's electrical flexibility: increasing variable production requires additional flexibilities, in particular hydrogen storage*

**In order to guarantee the supply-demand balance of the power system despite the decrease in production controllability introduced by the penetration of variable production means, it seems necessary to use additional flexibilities, ranging from the intradaily to the interannual scale**. However, apart from the interconnections between electrical networks, **hydrogen appears to be the option that allows for longer term flexibilities, on production through storage but also on consumption through the control of electrolysers** (RTE, 2022). This storage solution is known as *power-to-gas-to-power*, i.e. the energy loop consisting of producing hydrogen gas from electricity by electrolysis, and then recovering part of the energy in the form of electricity by combustion in a thermal power plant or oxidation in a fuel cell. A variant exists, not treated in this study, which consists in transforming hydrogen into methane by a process of methanation. If this were the preferred option instead of electricity production from hydrogen, the following reasoning would remain unchanged and only the required volumes of hydrogen would be slightly increased due to the additional energy losses occurring during the methanation process.

RTE[69] conducts numerous prospective works concerning the French power system and its studies deal with flexibility needs according to future electricity production scenarios. **We have used RTE's work to analyze the hydrogen needs for electricity production according to the coverage rate of**

[68] PSH: Pumped Storage Hydropower.
[69] RTE: Réseau de Transport d'Électricité, manager of the public high-voltage network in metropolitan France.

**wind and photovoltaic power**. We observe that in France, in 2050, and in a context of achieving national carbon neutrality, **the production of electricity by hydrogen, and therefore its storage, is necessary from a joint penetration rate of wind and photovoltaic located around 50%. After this threshold, the need for hydrogen increases in a very linear way with their coverage rate**.




*Sources: (RTE, 2021). The points correspond to the situations in 2050 of the 6 scenarios studied by RTE, which differ, among other things, in the level of development of wind power and photovoltaics.*
*Notes: (1) 30 $TWh_{LHV}$ of $H_2$ allow to produce about 15 TWh of electricity, compared to about 680 TWh (between 654 and 713) of production forecast in the RTE scenarios. These values do not take into account potential biogas electricity production, which is an additional means of flexibility. | (2) Strictly speaking, variable renewable energies include other means of production, which are in the minority in these projections.*

## *Tomorrow's electricity storage: what place for hydrogen?*

**The 1.5°C scenarios selected and studied by the IPCC show a coverage by wind and photovoltaics of up to 40% in 2030 and 60% in 2050 on a global scale** (IPCC, 2018). **The application of the relationship drawn from the work of RTE would lead to a zero need for electricity production from hydrogen in 2030 and a need of 23 $MtH_2$ in 2050** considering the average electricity production of these scenarios (62,500 TWh) and a 50% efficiency for electricity production[70] from hydrogen.

However, applying the lessons of RTE's analyses to a geographical area such as the world does not make physical sense, as there is no globalized power grid. Moreover, an average value hides disparities on a smaller scale, and even if the average rate of wind and photovoltaic remains below 50% in 2030, it is possible that this is not the case for some specific geographies that might then need hydrogen as an electricity storage solution (non-interconnected areas without hydroelectricity for example). The study of the coverage rates of variable means and electricity production volumes on a regionalized scale allows a more accurate vision of hydrogen storage needs.

By considering **regionalized scenarios that imply a very significant development of wind and photovoltaics, it is possible to find higher and probably increasing hydrogen volumes**. IRENA's work

[70] RTE indicates that the thermal power plants envisaged to produce electricity from hydrogen in the case of France have efficiencies ranging from 40% (combustion turbines) to 60% (combined cycle gas turbine). Source: RTE, 2022.

allows for this type of analysis, projecting global "modern" electric renewable electricity volumes and coverage rates segmented into 10 geographic areas (IRENA, 2020). **The application of the relationship drawn from RTE's work to IRENA's projections results in volumes of around 9 $MtH_2$ in 2030 and 55 $MtH_2$ in 2050**, again considering a 50% efficiency.

It is important to note that **these results are subject to strong assumptions and uncertainties**. First, **while regionalization allows for a much finer analysis, it is not yet faithful to the physical reality** of electricity networks and their interconnections. Furthermore, **the IRENA scenarios are likely to be part of an ambitious trajectory of limiting greenhouse gas emissions and limiting energy consumption**, leading to projected electricity production volumes that are lower than the average of the 1.5°C scenarios retained and studied by the IPCC. These two elements lead to say that the necessary volumes of hydrogen could be higher than those found. On the contrary, **the IRENA scenarios are very voluntaristic on the development of renewable energies**, especially variable production, and reach rates of renewable coverage well above the average of the 1.5°C scenarios retained and studied by the IPCC. Moreover, **due to the lack of disaggregated data, the calculations were made with the renewable energy rates that IRENA calls "modern", which are not all variable** because they probably include other modes of production such as hydroelectricity. These two elements lead to the conclusion that the required volumes of hydrogen could be lower than those found.

Based on the elements discussed in this section, it appears that **the need to mobilize hydrogen to store electricity through the *power-to-gas-to-power* loop will depend on the direction taken regarding the development of variable electricity production means, primarily wind and photovoltaic**. As long as these modes of production remain in the minority, hydrogen storage should not be essential; on the contrary, it will certainly become indispensable if these modes of production become the majority. Most likely, the future situation will differ from one power system to another, with some having hydrogen needs as early as 2030 while others may wait until 2050 or later. In any case, **hydrogen needs for electricity production should not exceed about 10 million tons by 2030**.

# Overview and conclusions

## Relevance analyses within the studied uses

: We have summarized the results for each use in the table below. It is possible to identify **a first categorization as to the relevance of hydrogen consumed by 2030 in the different uses**, based on the following criteria:

- **The unitary decarbonization potential of hydrogen within use.** This indicator represents the decrease in emissions induced by the production of a unit (such as 1 ton of steel, 1 $m^3$ of refined oil, or a ton-kilometer transported) by the low-carbon hydrogen pathway instead of the currently generalized fossil pathway (e.g. BF-BOF pathway for steel, hydrogen produced by steam reforming for refining or kerosene for air transport);
- **The possible time horizon for the deployment of the solution.** The **relevance of hydrogen is evaluated here for its consumption in 2030**: it is therefore possible that some solutions are not mature enough, technologically speaking, to be deployed in this time frame. On the contrary, for some uses, low-carbon hydrogen could already be deployed but the decrease in the sector's activity suggests a decreasing demand for hydrogen: this is the case for refineries;
- **Decarbonizing solutions that are complementary or competitive with low-carbon hydrogen.** This indicator makes it possible to determine whether hydrogen is necessary for the use considered: hydrogen will not have the same role to play in the case where no alternative exists or if they cannot decarbonize the use on their own, as in the case where there are more efficient solutions on the criteria of cost and emission reduction, and which could be generalized.

Finally, **other qualitative considerations were considered**, not recalled here but developed in the previous chapter of this report (for example the toxicity of ammonia as a marine fuel, or the different arguments in favor or against hydrogen for each use).

| Sector | Application | Relevance of low-carbon $H_2$ | Unit decarbonization potential[1] | Time horizon | Decarbonizing alternatives, complementary or competing | Low-carbon $H_2$ potential in 2030: upper limit ($MtH_2$) |
|---|---|---|---|---|---|---|
| Industry | Ammonia production | ✓ | ~73% | ⧗ | CCS on the production site | 5 |
| Industry | Methanol production | ✓ | ~70% | ⧗ | | 10 |
| Industry | Steel: $H_2$ DRI | ✓ | ~76% | ⧗ ⧗ | CCS on the production site, scrap recycling pathway with electric furnace, gas based direct reduction of iron | 3 |
| Industry | Steel: injection in BF-BOF | ✗ | ~14% | ⧗ | | n.a. |
| Transportation | Railway | ✓ / ~ | ~78% | ⧗ ⧗ | Direct electrification of railways, batteries | 3 |
| Transportation | Trucks | ~ / ✗ | ~70% | ⧗ ⧗ | Batteries, BioNGV, 2G biofuels | 4 |
| Transportation | Maritime: $LH_2$ | ✗ | ~66% ~89% | ⧗ ⧗ ⧗ | Bioenergy : 2G bioliquids and 2G BioLNG | n.a. |
| Transportation | Maritime[2]: e-ammonia | ~ | ~39% ~60% | ⧗ ⧗ | | 6[3] 30[3] |
| Transportation | Maritime[2]: e-methanol | ✓ | ~50% ~78% | ⧗ | | 8[4] 20[4] |
| Transportation | Maritime[2]: e-LNG | ✓ | ~53% ~79% | ⧗ | | 4[3] 15[3] |
| Transportation | Short- to medium-haul aircraft: direct use | ✗ | ~66% | ⧗ ⧗ ⧗ | Batteries, biofuels | n.a. |
| Transportation | Aviation: synfuels | ✓ | ~62% | ⧗ ⧗ | | ~0 |
| Energy | Mixed consumption in gas networks | ✗ | ~4% | ⧗ | Renewable methane, Dedicated low-carbon hydrogen networks | n.a. |
| Energy | Storage for the electrical system | Necessary if many variable renewables | n.a. | ⧗ ⧗ | Electricity interconnections, Hydraulic tanks | 9 |
| Energy | Refining | ~ | ~15% | ⧗ Transition | CCS on the production site | 25 |

*Notes: (1) For marine fuels, the high range corresponds to a variant using very-low-carbon hydrogen, at 1 $kgCO_2e$ / $kgH_2$ , i.e. electrolysis from electricity with a carbon content around 20 $gCO_2e$ / kWh. In addition, more optimistic assumptions have been made for e-LNG regarding leakage rates and energy consumption for liquefaction. | (2) The 3 potentials for the maritime sector do not add up: they correspond to the potentials for 3 variants of a decarbonization scenario for the sector, each of which favors a synthetic fuel. These scenarios are described in the notes below. The range corresponds to the results according to whether we assume a high or low availability of 2G biofuels. | (3) The e-LNG (resp. e-ammonia) scenario considers that new engines dedicated to synthetic fuels will run exclusively on e-LNG (resp. e-ammonia) by mobilizing the volumes of hydrogen represented in the last column. This scenario also foresees an additional consumption (not represented here) of 5 $MtH_2$ for the production of e-methanol, used as fuel for retrofitted fleet units. | (4) The e-methanol scenario foresees only the use of methanol, for retrofitted units and new engines.*

**The upper limit of the low-carbon hydrogen potential** (here in the last column) echoes the various models presented in each of the sectoral sections of the report. **This value represents for each sector the global amount of low-carbon hydrogen to be mobilized in order to respect the evolution of greenhouse gas emissions that is compatible with the Paris Agreement while keeping up with the growth of the activity.** As the total amount of hydrogen to be mobilized is very large, it is likely that **the relevance of activity projections to carbon budgets will** have to be **re-examined**, or vice versa. This is why this potential is **referred to as the "upper limit".**

**For marine fuels, the unitary decarbonization potential is presented as a range to illustrate the variability that can result from the use of a hydrogen that is even less carbon intensive** than the threshold for low-carbon hydrogen that we have retained in this study. This **very low-carbon hydrogen was considered at 1 $kgCO_2e$ / $kgH_2$**, rather than 3 $kgCO_2e$ / $kgH_2$, which is the value chosen for the low-carbon hydrogen in the study. To be low-carbon, hydrogen by electrolysis must be produced from electricity with a carbon content lower than 20 $gCO_2e$ / kWh, which is possible with electricity from wind and nuclear sources, and under certain conditions for hydro and photovoltaic electricity[71].

[71] Concerning hydroelectricity by water retention, important greenhouse gas emissions can take place due to the flooding of vegetation, which then decomposes notably in the form of methane (a case that can happen at tropical latitudes). For photovoltaic electricity, it is possible to get close to such a carbon footprint for particularly sunny locations, and/or for panels whose production is less carbon intensive than average.

A sensitivity analysis was conducted on marine e-fuels with hydrogen at 1 $kgCO_2e$ / $kgH_2$ for the high range. The analysis for e-LNG also went further with lower assumptions for methane leakage and electricity consumption for liquefaction. Without these favorable assumptions, the high range, thus mobilizing hydrogen at 1 $kgCO_2e$ / $kgH_2$, would be around 79% for e-LNG.

Due to the lack of in-depth assessment, the use of industrial heat is not represented in this table. It should be noted here that hydrogen does not show any particular advantage over its competitors for this use, so it is very unlikely that it will become the main decarbonization option for the sector. According to a recent study by the Hydrogen Council, the use of hydrogen in this sector would be low, around 2 $MtH_2$ in 2030.

Based on these criteria, we distinguish relevance into the following three categories:

- **The no-regrets pathways** (green icon in the table), which represent a **total potential of about 25 to 30 $MtH_2$:** there is no arbitration to be made on how to decarbonize the use and hydrogen is unavoidable in the medium and long term, for example because for the use in question it is the only existing lever for reducing emissions, or because the other levers alone will not be sufficient;
- **Potentially relevant uses but where some uncertainties remain** (orange icon in the table), for several different reasons: low-carbon hydrogen leads to too little emission reduction, its development still depends on potential/future technological advances or simply some existing solutions have better performances regarding these two criteria. For all these reasons, there might not be any hydrogen in these uses, and if there is, then its role will probably be in the 2$^{nd}$ foreground compared to one or more other decarbonizing solutions. This category represents **a total potential of about 25 to 40 $MtH_2$** (the range is important, because of the rail and truck uses that we have not univocally categorized on the one hand, and because of the variant in the maritime sector that we have retained on the other hand);
- **The uses for which hydrogen is simply not relevant** (red icon in the table) as a decarbonizing solution.

# Analyses of relevance between the uses studied

**Still with the prism of a medium-term deployment of low-carbon hydrogen in the world, which means the consumption of hydrogen in 2030 in our study**, we then **evaluated the different uses between them, with a view to a constraint on the total volume of low-carbon hydrogen available at this time horizon**. This volume constraint can result from a limit in the amount of investment, in the available low-carbon electricity, or more simply from delays in the deployment of projects. Given this constraint, it is not enough to analyze the relevance of hydrogen within each use to choose how to allocate the available quantities. The question we wish to answer is: if the volume of low-carbon hydrogen is limited, **for which uses should it be allocated in priority?**

We propose a way to answer this question, again in the light of the need to reduce greenhouse gas emissions. To do so, **we evaluate the different uses based on a metric: the decarbonizing intensity of hydrogen**. This metric, expressed in $tCO_2e$ / $tH_2$, translates the reduction of the carbon footprint (expressed in $tCO_2e$) of a use that low-carbon hydrogen allows, compared to a unit of hydrogen (expressed in $tH_2$). **Crossing this decarbonizing intensity with the potential of low-carbon hydrogen allows us to arrive at an emission reduction potential in 2030**, use by use. These results are represented in the table below for the relevant and potentially relevant uses by 2030.

| | | Low-carbon $H_2$ potential in 2030: upper limit ($MtH_2$) | Decarbonizing intensity of low-carbon $H_2$ ($tCO_2e$ / $tH_2$) | Emissions reduction potential in 2030[1] ($MtCO_2e$) |
|---|---|---|---|---|
| Industry | Ammonia production | 5 | 12,5 | 60 |
| Industry | Methanol production | 10 | 10 | 100 |
| Industry | Steel: $H_2$ DRI | 3 | 24 | 75 |
| Transportation | Railway | 3 | ~8[2] | 25 |
| Transportation | Trucks | 4 | 8 | 30 |
| Transportation | Maritime[3]: e-ammonia | 6-30[4] | 4 | 25-100[4] |
| Transportation | Maritime[3]: e-methanol | 8-20[5] | 5 | 40-100[5] |
| Transportation | Maritime[2]: e-LNG | 4-15[4] | 6 | 25-90[4] |
| Transportation | Aviation: synfuels | ~0 | 6 | ~0 |
| Refining | | 25 | 10 | 250 |

*Notes: (1) The reduction potential is the product of the potential volume of low-carbon hydrogen in 2030 with the decarbonizing intensity. The values have been rounded to the nearest 5 $MtCO_2e$. | (2) For the rail sector, this is an order of magnitude value, due to the lack of robust data on the performance of diesel locomotives. | (3) The 3 potentials for the maritime sector do not add up: they correspond to the potentials for 3 variants of a decarbonization scenario for the sector, each of them favoring a synthetic fuel. These scenarios are described in the notes below. The range corresponds to the results according to whether we assume a high or low availability of 2G biofuels. | (4) The e-LNG (resp. e-ammonia) scenario considers that new engines dedicated to synthetic fuels will run exclusively on e-LNG (resp. e-ammonia) by mobilizing the volumes of hydrogen represented in the last column. This scenario also foresees an additional consumption (not represented here) of 5 $MtH_2$ for the production of e-methanol, used as fuel for the retrofitted units of the fleet. | (5) The e-methanol scenario foresees only the use of methanol, for the retrofitted units and new engines.*

The variability in the values of decarbonizing intensities between uses may seem high. We give here **some explanations for some particular cases**:

- **For steel**: the decarbonizing intensity for direct reduction **is very high compared to all other values**. This is due to the fact that hydrogen is used **as a feedstock to avoid "wasting" carbon in the production of steel**. In fact, in the classic blast furnace process, the iron ore is first transformed into cast iron, with a too high concentration of carbon, coming from coal, compared to the steel required. This cast iron is then passed through an oxygen furnace to reduce the carbon concentration (causing $CO_2$ emissions). The hydrogen thus contributes to a more "efficient" reduction of the iron ore;
- **For ammonia production, methanol production and refining**: the decarbonizing intensities are not exactly the same (in particular for ammonia which has a higher decarbonizing intensity), while in all three cases it is a question of replacing a fossil hydrogen with a low-carbon hydrogen. **The differences are explained by the fact that the carbon content of fossil hydrogen is higher or lower in the reference situation**. For example, for ammonia

production, one third of the fossil hydrogen consumed comes from coal gasification, a more carbon intensive process than steam methane reforming;

- **For trucks, compared to maritime**: the decarbonizing intensities are low for maritime fuels, especially for e-ammonia, compared to the use of hydrogen for trucks. However, for all these uses, it is a substitute for diesel fuel (admittedly of a slightly different nature between ships and trucks, but this plays a role at the margin). The differences come from the fact that **engine efficiency is better for ships in the reference situation** (which reduces the decarbonization potential because less fossil carbon is "wasted"), that the **step of transforming hydrogen into e-fuel increases the carbon footprint**, and that **the combustion of e-fuels is accompanied by the combustion of a pilot fuel in ship engines**. Finally, and this has a very significant impact on e-ammonia, **the reduction in emissions for marine fuels takes into account the lower volumetric energy density of these fuels compared to fossil marine fuel** (this is the reasoning in "fossil equivalent energy" which is explained in the section on marine).

By comparing the decarbonizing intensities between the different uses, we can identify **2 complementary analyses to those above:**

1. For the use of hydrogen in the form of **e-ammonia in the maritime sector**, or directly as **fuel for trucks and trains**: **used for these uses, hydrogen does not have a very high decarbonizing intensity** compared to other uses considered. From a carbon point of view, **these are therefore not uses to be developed in a situation where there is a limited volume of hydrogen**, as will probably be the case by 2030;
2. For **refining**: even if the use of low-carbon hydrogen has a low unitary decarbonization potential (within this use), **the decarbonization intensity is relatively high compared to the other uses studied**, and **above all it is a use for which low-carbon hydrogen has a very important emission reduction potential in absolute value**. This is obviously explained by the fact that the potential volume of low-carbon hydrogen use is itself very high, as refining is already the leading consumer of hydrogen in the world.

Finally, we have not included the values in the above table for the uses considered irrelevant by 2030, but we nevertheless mention that **the value for the injection of hydrogen as an auxiliary reductant in blast furnaces (11 $tCO_2e$ / $tH_2$) is unsurprisingly lower than the direct reduction by hydrogen, which is all the more reason to favor this second process**. Finally, **for the consumption of hydrogen as a mixture in gas networks, the value is low in absolute terms** (less than 5 $tCO_2e$ / $tH_2$), **which further reinforces the assessment of this use as irrelevant**.

# Conclusions

These analyses of the relevance of hydrogen within and between uses lead to the following conclusions, with a view to reducing greenhouse gas emissions:

- **The ammonia and methanol sectors will need (and may already have) access to the low-carbon hydrogen they need to get closer to their climate targets**. However, this lever may not be sufficient to meet emission reduction targets, making it likely that lower volumes of activity will be required to meet carbon budgets, even with the joint development of carbon capture and sequestration (CCS);

- **The steel** (direct reduction) **and maritime** (for e-LNG and e-methanol synthetic fuels) **sectors will necessarily need low-carbon hydrogen in the medium term to follow their 2°C trajectory.** For these two sectors, hydrogen is both essential and complementary to other solutions: the development of recycling and CCS for steel, and bioenergy for maritime. For marine fuels, e-LNG can be easily used in existing or new LNG ships to reduce greenhouse gas emissions and save natural gas;
- **The aviation sector will also need access to low-carbon hydrogen for synthetic fuels, again as a complement to bioenergy, but in the longer term:** the potential volumes in 2030 are almost zero. **Hydrogen for direct use in aviation will not see the light of day before 2035** because the technologies are not mature enough;
- **The use of hydrogen as a flexibility brick for electrical systems will probably be unavoidable**, in the medium term and especially in the long term, to accompany the development of variable electricity production means, such as wind power and photovoltaic panels.
- **Refineries could benefit from the use of low-carbon hydrogen now**, even if the **reduction in emissions is proportionally low.** It is likely that **CCS is a pathway that better fits the needs of the sector**, even if its decarbonization cannot be entirely based on this solution (limited accessibility to deep geological storage). An allocation of hydrogen in this sector must be made taking into account the necessary decrease of the volumes of activity of the sector over the coming decades;
- **For railways and trucks, the use of hydrogen is relevant but in limited quantities for certain specific situations** (e.g., a strong need for autonomy, or in the form of hybridization between batteries and hydrogen within the same vehicle). These sectors **will be decarbonized through electrification**. Although the unitary decarbonization potential of hydrogen is high in these sectors, the **decarbonization intensity of hydrogen is low**. It is then **preferable to use low-carbon hydrogen for other uses**;
- **Concerning the production of ammonia as a synthetic fuel for the maritime sector**: there are still **uncertainties about the technology on the** one hand (incomplete combustion leading to nitrous oxide emissions and toxic ammonia leaks) and above all, **as the decarbonizing intensity is lower than that of other fuels, it is preferable to use low-carbon hydrogen for other uses**, whether for the production of the other synthetic fuels studied within the maritime sector, or in other sectors;
- **The consumption of hydrogen in gas networks and the injection of hydrogen in blast furnaces are not relevant applications of hydrogen**, because they do not generate enough emission reductions in their sectors. The decarbonizing intensity of these uses is also low, in absolute terms for hydrogen consumption in gas networks, or compared to the direct reduction of iron ore in the case of the steel industry.

It is **important to remember that these conclusions must be read in the context of the temporal scope of the study, which focuses on low-carbon hydrogen consumption in 2030**. Given the future developments in the deployment of hydrogen, but also complementary or competing decarbonizing solutions, **the longer term potential is not necessarily in keeping with the medium term assessment**. Especially considering the inertia (of the industrial system, vehicle fleets, etc.), hydrogen can spread more or less quickly in the uses. To illustrate this point, let's take the case of air transport: the potential of low-carbon hydrogen in this sector in 2050 is still very uncertain, although we venture an assessment in this report. But by 2030, the sector's hydrogen consumption will still be very marginal, which in itself says nothing about the potential for 2050.

**Carbone 4** is the first independent consulting firm specialised in low carbon strategy and adaptation to climate change.

We are constantly on the lookout for signs of weakness, we deploy a systemic vision of the energy-climate constraint and put all our rigour and creativity to work in transforming our clients into climate challenge leaders.

Contact: contact@carbone4.com