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Low-carbon hydrogen, a key element in decarbonising heavy industry and transport



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When discussing energy decarbonisation, **the first solution that comes to mind is gradual electrification of all energy-consuming sectors**: building heating, vehicles, industrial processes, etc. As electricity is (or will be depending on the country) increasingly decarbonised thanks to the development of renewable energies or nuclear power, this should significantly reduce greenhouse gas emissions. **This is of course true, but only within a certain limit**.

Because not all sectors are easily electrifiable. In heavy industries, chemicals or the steel industry for example, energy must often be supplied in the form of a chemical reagent or a flame; hence requiring energy in molecular (liquid or gaseous) form, rather than as electrons. **Heavy transport by land, sea and air** is also difficult to electrify, for another reason: the main problem is the insufficient energy density of current batteries, despite continuous improvements. On this criterion, the advantage of liquid fuels is now immense compared to electrified transport. The second problem is their charging time, which is not always compatible with the constraints of operation and profitability.

Today, gaseous or liquid energy carriers are unfortunately mostly fossil-based (natural gas, hydrocarbons). **One of the challenges of the Energy Transition is to develop gaseous or liquid energy carriers of renewable origin**. This is the case for biomethane and biofuels. However, we already know that the biomass resources used to produce these biomolecules will not be sufficient to meet the demand of non-electrifiable sectors.

This is where the hydrogen molecule comes into play! Provided that the hydrogen is **produced without CO2 emissions**. Because depending on how it is manufactured, greenhouse gas emissions vary greatly. To simply, we talk about different types of hydrogen by assigning them colours.

I. The different types of hydrogen based on their production method

When hydrogen is produced **from fossil-primary energy sources** (typically coal or natural gas), it is referred to as **brown or grey hydrogen**. This remains almost the exclusive method for producing hydrogen used as a chemical reagent in fertilizer or chemical industries. Globally, of the 97 million tonnes of hydrogen consumed annually for applications such as refining, steel production, and the manufacture of ammonia and methanol, 99% is produced from fossil fuels. Using brown or grey hydrogen as a new energy vector is therefore ineffective, since it emits as much CO2 during its life cycle as the fossil energy used to produce it. The only difference is that it emits this CO2 at the time it is manufactured and not at the time it is used.

Conversely, producing hydrogen without emitting CO_2 is highly beneficial for the Energy Transition, because we then have a **storable and carbon-free energy vector.**

To manufacture this "low-carbon" hydrogen (*), two solutions are possible.

The first is to produce it **with fossil fuels, but by capturing the CO2** at the time of its production (which is not very complicated because it comes out of the production process very concentrated); the hydrogen produced can then be described as "low-carbon"; this is called **blue hydrogen**. The advantage of this production sector is that it is very competitive, since it can produce low-carbon hydrogen at less than €2 to €2.50/kg. The disadvantage is that the captured CO2 needs to be used close to the production site, or stored underground (which is rarely the case), or transported to a centralized storage site (which requires heavy infrastructure).

The other way to **produce low-carbon hydrogen is to use renewable energy**. The most popular method today is water electrolysis. An electrolyser dissociates water molecules from electrical energy, producing hydrogen and oxygen simultaneously. The CO2 emissions associated with this method of hydrogen production are those of the electricity that powers the electrolyser. Hydrogen is therefore low-carbon if the electricity is low-carbon, therefore renewable (hydraulic, wind, photovoltaic) – this is called **green hydrogen** – or of nuclear origin – we sometimes call it **pink hydrogen**. Hydrogen produced by electrolysis is currently the main way to massively produce low-carbon hydrogen for the Energy Transition. The major disadvantage of this sector is that the cost of production is **4 to 5 times more expensive than blue hydrogen**, unless you have a very competitive source of green electricity, or consider additional revenues, for example by enhancing the flexibility of electrolysers (load shedding possible during peak hours). But the advantage of electrolysers is that they can be installed on a **decentralised scale** (a few MW), close to consumption sites, which **avoids or at least reduces transport costs**.

Finally, if hydrogen is formed naturally in the subsurface, it is called **white hydrogen**. But let's leave this subject aside for the moment because the search for natural hydrogen that can be sourced underground is still at a very preliminary stage.

It's important to note that colour coding is a simplification for public communication. For the European Commission, the only metric that matters are the actual CO2 emissions of hydrogen during its life cycle: hydrogen is considered **low-carbon** if emissions are below 3.38 kg CO_2 per kg of H_2. Otherwise, it's not a low-carbon energy carrier.

II. The main advantages and disadvantages of low-carbon hydrogen as an energy carrier

The major advantage of low-carbon hydrogen compared to other decarbonized energy carriers is that it **can be stored**, unlike intermittent renewable electricity. Furthermore, its **energy density per unit mass is high**: one kilogram of hydrogen contains twice the energy of one kilogram of biomethane, and three times that of gasoline. Another advantage is that hydrogen can be used directly in combustion processes or easily **converted** into other energy carriers: **electricity** (via fuel cells) or gaseous or liquid energy carriers such as **synthetic methane, synthetic kerosene, ammonia, ethanol, etc.** Thus, hydrogen can be used in vehicles or industrial processes or be transformed into liquid fuels for aviation (SAF) or maritime transport, making it crucial for decarbonising the most difficult sectors.

On the other hand, its **density is very low**, which means that it must be **compressed to several hundred bars** for storage or use, which increases the complexity and cost of infrastructures. For instance, hydrogen is transported by truck at pressures between 150 and 250 bars, stored in light vehicles tanks at a pressure of 700 bar and in heavy vehicles at 350 bar.

Overall, **the cost of low-carbon hydrogen remains high** for several reasons. Firstly, it is **produced from another energy**, making it inherently **more expensive** than this initial energy due to transformation costs. As the energy efficiency of electrolysers and fuel cells is currently poor, these **conversion costs are high**. The second reason is that, in addition to production costs, compression costs must be added as explained above. Finally, it is a **young sector** that does not yet benefit from the economies of scale that we already have for other green energies that are already widely developed.

III. The sectors where low-carbon hydrogen is most promising

<u>The first market expected to adopt low-carbon hydrogen is heavy industry</u>. At first instance, this means to decarbonise all sectors of the chemical industry, which currently uses grey or brown hydrogen as a chemical reagent. These include the manufacture of nitrogen fertilisers, which today use large quantities of fossil natural gas, and other manufactures of synthetic molecules using hydrogen as a basic reagent, such as methanol. Hydrogen is also widely used as a chemical input in steelmaking and refining. As previously mentioned, these applications represent 97 million tonnes of hydrogen consumption globally, which must gradually shift to low-carbon hydrogen, including 7 to 8 million tonnes within Europe This **market for replacing brown or grey hydrogen** with low-carbon hydrogen is the least difficult to develop because it **does not require heavy investment by manufacturers** who already consume hydrogen. The main problem, which is far from negligible, is the **additional cost of low-carbon hydrogen**.

Beyond chemical applications, new significant quantities of low-carbon hydrogen will be needed to decarbonize heavy industry sectors such as steelmaking, glass manufacturing, and road asphalt production. The Swedish steelmaker SSAB, for example, has developed a process using hydrogen for direct iron ore reduction to produce low-carbon steel. The car manufacturer Mercedes has already positioned itself as a buyer of this carbon-free steel for its range of clean vehicles.

The second key market for low-carbon hydrogen is heavy transport. Low-carbon hydrogen can directly power trucks and other heavy vehicles with an **electric motor**, **replacing batteries with hydrogen tanks under pressure and a fuel cell**. This solution is more attractive than batteries because recharge **times** are much shorter with hydrogen and the **volume and weight of batteries in heavy-duty vehicles is often prohibitive.** There is already a range of hydrogen-powered heavy vehicles: trucks, buses, garbage trucks. For example, in Switzerland, about fifty Hyundai fuel cell trucks are already on the road. Regarding city buses, many local authorities are testing hydrogen buses. This is true in Europe: Dijon, Auxerre, Pau, Le Mans, Versailles, Rouen, Bologna, Venice, Köln, Frankfurt, Duisburg... etc... This is also true outside Europe. This is evidenced by the announcement in July 2024 by the South Korean government that the number of hydrogen-powered buses had reached 1,000 units, up from 650 in 2023, with a national ambition to deploy more than 20,000 hydrogen buses by 2030.

But the ***competition between battery-powered and hydrogen-powered heavy-duty vehicles is far from over.*** Because the progress of batteries is rapid: their characteristics have evolved in about ten years from 100 to 250 Wh/kg in terms of specific energy, and their volume density has increased from 100 Wh/l to 450 Wh/l. The significant R&D efforts carried out by all players in the field should lead to exceeding 300 Wh/kg and 600 Wh/l, gradually increasing the share of the heavy truck market accessible to electric battery technology. However, ***the duration of the recharge*** will remain ***difficult to compress***.

Finally, it should be remembered that there is another way to use hydrogen for transport: the **manufacture of e-fuels**. An e-fuel is a liquid synthetic fuel produced from hydrogen obtained by electrolysis, therefore from electricity (hence its name), and which is a solution to contribute to the decarbonisation of the aviation and maritime sectors. For air transport, the European "***Refuel Aviation»*** regulation requires the gradual incorporation of a minimum proportion of sustainable fuels (the famous SAF or Sustainable Aviation Fuels): at least 2% in 2025, 6% in 2030, up to 70% in 2050. To meet this requirement, the IEA (International Energy Agency) believes that biofuels will not be enough (insufficient quantities of biowaste) and that **e-kerosene** will have to be produced in addition**.** For maritime transport, in the longer term, it will be **e-methanol** or **e-ammonia.**

These e-fuels are currently significantly more expensive than fossil fuels and even biofuels, but **if we think in terms of the additional cost of the final product, the impact should be put into perspective**. The IEA estimates that with 10% of e-kerosene incorporation in aviation fuel by 2030, the increase in the price of the plane ticket would be only 5%. And for shipping, the cost of ownership of a container ship powered by 100% e-ammonia or e-methanol would be 75% higher than that of a conventional container ship running on fossil fuels. While this is a substantial increase, the additional cost would only be 1-2% of the average value of goods transported in containers.

Energy companies are already investing in these e-fuels. For example, Total-Energies and Engie have signed a cooperation agreement to develop a hydrogen production site capable of supplying five tonnes of green H2 per day in La Mède (Châteauneuf-les-Martigues). This facility will be able to meet the needs of the green fuel production process of Total-Energies' biorefinery. The 40 MW electrolyser will be powered by solar farms. In addition to this particular installation, nearly 200 industrial pilots worldwide are currently being studied.

The third energy application of low-carbon hydrogen is the storage of renewable electricity. The idea is to transform the green electricity that we want to store into hydrogen, by electrolysis. The green hydrogen produced in this way is then stored for a day, a week, or several months, and then transformed back into electricity by a fuel cell. On paper, the concept is very attractive for long-term storage (several days, or even several months) of intermittent electricity on a grid scale. However, given the current energy efficiency of electrolysers and fuel cells, the overall efficiency of the operation is only 30%, which is very insufficient. For the time being, this storage application is therefore reserved for very specific cases such as the supply of renewable electricity to islands (in the West Indies for example), or in countries where the variability of the price of electricity is such that we can live with storage with mediocre efficiency.

IV. The conditions necessary for the massive development of low-carbon hydrogen uses

As we have just seen, there are potentially many uses of hydrogen as a carbon-free energy carrier. But the development of hydrogen in the priority markets that have just been swept is **still in its infancy**. Admittedly, **industrial pilot installations** are multiplying, and we regularly see new announcements **of experiments with fuel cell vehicles** by transport operators or household waste collection vehicles. These experiments are made possible by European and national **financial aid.**

But for this new sector, which is essential to achieving the objectives of the Paris Agreement, to develop significantly, there are **several prerequisites**.

The first is the availability of enough decarbonated electricity to power the electrolysers, at reasonable cost.

For example, if we want to decarbonise by 2035 all the grey or brown hydrogen that we consume each year in France (about 1 million tons), we would need a quantity of electricity of about 50 TWh, or 11% of current French electricity consumption, which is about 450 TWh. This figure is not **incompatible** with the new trajectory of increasing French electricity consumption to achieve our objectives of reducing fossil fuels, which is between 580 and 640 TWh in 2035, i.e. an increase of between 130 and 190 TWh. But the overconsumption linked to the decarbonisation of hydrogen would put an additional strain on the volumes of electricity available to decarbonise other sectors. **So choices will have to be made.**

The second prerequisite is **to move all the links in the hydrogen value chain forward at the same speed.** For hydrogen to be used by an industrial company or to run a hydrogen vehicle, there must be electrolysers and fuel cells, along with the means to supply them with electricity, to store the hydrogen, deliver it (by truck or pipeline), purchase a hydrogen furnace or process, or supply fuel cell-powered vehicles. It is therefore true **regional ecosystems** for the production, transport, distribution, storage and use of hydrogen that must be put in place. In the long term, we need to create infrastructures that are equal to the challenges: electrolyser and fuel cell manufacturing plants (gigafactories), storage and transport infrastructures on a European scale, hydrogen refuelling stations on major European roads, etc. not to mention the strengthening of renewable electricity production means.

This is why more and more French and European project tenders are favouring **territorial ecosystems**, which are both significant in size and bring together the main players in the different links in the chain (producers, customers, technology suppliers, supply chain players, etc.), in order to **concentrate public aid on projects that are both cross-cutting and large-scale.**

Provided that these conditions are met, and the necessary subsidies are obtained, **it is already possible to set up interesting projects for the Energy Transition and that can be financed with controlled risks.**

This is the case, for example, with Lhyfe's recent announcement of the signing of a financing in which the Sienna Sustainable Infra Debt III fund participated for the construction of 30 MW of electrolysers spread over 4 sites (3 in France, 1 in Germany), making it possible to produce a total annual quantity of hydrogen of more than 3500 tons per year. From its launch, this project includes not only hydrogen production, but also electricity sourcing, the first contracts with offtakers and the entire necessary logistics chain.

Another high-stakes project announced in early 2025 is the Toyota Motor Europe, Hydrogen Refueling Solutions (HRS) and ENGIE partnership to deploy a new generation of hydrogen refuelling system, faster and more economical. Toyota's Twin Mid Flow technology accelerates charging and significantly reduces investments in hydrogen stations. This partnership aims to contribute to the development of road uses of hydrogen in Europe by installing hydrogen stations accessible to the public every 200 km, along the Trans-European Transport Network (TEN-T).

V. Global and European perspectives for the development of hydrogen in the Energy Transition

In its NetZero scenario, the International Energy Agency has set the **ambition of doubling global hydrogen production by 2030** to 200 million tonnes per year, **70% of which would be low carbon**. This would make it possible to decarbonise a good part of the hydrogen currently used as a raw material for industry, the remainder being used as low-carbon energy in other priority markets, either directly or to make e-fuels.

These figures are two **of the IEA's ideal scenario**. But **the reality today is far from this ideal**. Because the figures on the effective development of hydrogen in China, the USA and especially in Europe show a significant delay compared to the ambitions set out in the official strategies published. If these 3 regions do not quickly bring their actions in line with their strategies, we will be very far from the volumes necessary to achieve the objectives of the Paris Agreement.

The European example is particularly telling. The objective set by the European **RePowerEU** plan is to consume **20 million tonnes of renewable hydrogen by 2030**, with half produced in Europe and the other half imported. Yet, the sum of the production objectives announced by the 27 Member States only reaches about **6 million tonnes**. Spain is currently the most ambitious country, aiming for 1.2 million tons of production by 2030, followed by Germany with 1.09 million, Denmark with 0.66 million, and France and Portugal each targeting 0.6 million tons.

To reach the production target of 10 Mt/year in 2030, 100 GW of electrolyser capacity would need to be installed, requiring an annual growth rate of 150%. This is far higher than the 45% average annual growth observed since 2020. Although the project pipeline under development could technically allow the goal to be reached, investment decisions are being delayed due to the current economic context.

VI. Technological advances that could boost the use of hydrogen on a large scale

Today's main challenge is to **significantly reduce the production costs** of low-carbon hydrogen. This involves particularly lowering the costs of electrolysers while improving their performance. **Performance improvements are needed in terms of energy efficiency** to consume less electricity per kilogram of hydrogen produced, in terms of **equipment lifespan and availability** to lower maintenance costs, and in terms of **operational flexibility** to allow electrolysers to function under highly variable regimes when powered by intermittent renewable electricity.

Reducing the costs of electrolysers and fuel cells also involves developing more compact technologies that require fewer rare and expensive metals (e.g. for catalyst[1]).

Innovations to lower costs are not limited to improving electrolyser and fuel cell technologies. They also concern ***all links in the hydrogen production, transport and storage logistics chain***. Notable examples include the optimization and mutualization of transport and delivery logistics across multiple production sites (such as by Lhyfe), innovative underground hydrogen storage solutions using buried tubes (Vallourec), a demonstration project for hydrogen storage in salt caverns (Storengy), and retrofitting existing natural gas pipelines to transport hydrogen (NATRAN), etc.

These examples illustrate the dynamic nature of hydrogen R&D, a vital effort to bring this emerging sector to maturity. It is equally important that as many of these innovations as possible be European, so that our Old Continent remains in the technological and industrial race in this new sector!

In conclusion

It is important to reiterate that the IEA considers that the development of hydrogen not as a miracle solution, but as absolutely necessary for achieving the goals of the Paris Agreement. For hydrogen development to meet expectations starting from 2030, three conditions must be met: first, the availability of abundant, low-cost decarbonized electricity. Secondly, stability in public support policies for this nascent sector, and finally, a commitment from early adopters willing to engage in pioneering large-scale projects that will create market momentum through reference projects.

The current economic situation and international instabilities may lead to delay investments in decarbonisation solutions, especially the most innovative ones such as hydrogen. So there will likely be severe natural selection among the multitude of hydrogen projects that have been announced in recent years. This phase of refocusing on

[1] *Electrolysers dissociate water into oxygen and hydrogen, thanks to electrical energy; to facilitate this dissociation, it is necessary to add metallic elements called catalysts to the electrodes.*

the most resilient projects is a rather beneficial step, as those that make it to the final investment decision will constitute a strong portfolio of reference cases.

At the same time, technological improvements will be crucial to enhance the energy efficiency of electrolysers and fuel cells, reduce costs across all parts of the logistics chain, and build infrastructures adapted to future hydrogen demand. This will take time and significant financial resources, but it is worth the effort!

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