Hydrogen – Energy carrier of the future?

Holistic SWOT analysis

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1 Context and methodology

Over the past few years, **deep decarbonisation objectives** have been considered or announced in an increasing number of countries:

- European Union: -55% at the 2030 horizon (w.r.t. 1990 levels) and net zero in 2050
- United States: -50 to 52% by 2030 (with regards to 2005 levels) and net zero by 2050
- China: net zero by 2060
- Germany: net zero by 2045
- France: net zero by 2050

Indeed, the status of hydrogen has rapidly evolved over the past few years and this gas is now at the core of many deep decarbonisation strategies. Whilst it is generally recognised that energy efficiency efforts and the development of renewables can do most of the heavy lifting, a number of end-uses cannot be decarbonised via a direct electrification route. Hydrogen is one of the options to decarbonise these hard-to-abate sectors. However, different stakeholders have different views on the scope of the role of hydrogen, based on:

- Economic assessment of the trade-off between direct and indirect electrification routes
- Origin of hydrogen (electrolysis, pyrolysis, SMR + CCS, etc.)
- Role of alternatives (biomethane, CCS, etc.)
- Role of the gas infrastructure

In Europe, the **European Green Deal**[1], announced in late 2019, sets challenging objectives for the decarbonisation of the economy of the EU, and foresees an important role for hydrogen, especially in hard-to-abate sectors, but not only.

Multiple **policy initiatives** are being taken in order to ensure the hydrogen value chains scale up and can play their role in the decarbonisation of the economy. The European "**Hydrogen Strategy**"[2] proposes targets for the development of renewable hydrogen:

- 6 GW_e electrolysers by 2024 (1 MtH2 of renewable H2)
- 40 GW_e electrolysers by 2030 (10 MtH2 of renewable H2)

Numerous European **countries** have announced their own objectives for the development of electrolysis (far beyond what is announced in their NECPs):

- 6.5 GW in France by 2030
- 10 GW in Germany, 3 to 4 GW in the Netherlands, 2 to 2.5 GW in Portugal, 4 GW in Spain

Several **regions** in France and in other countries are developing hydrogen visions.

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[1] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[2] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

On the other hand, the deployment of electrolysers is subject to **rules and regulations** to mitigate the adverse impacts of uncoordinated developments

- The revision of RED II and the potential extension of the RFNBO requirement (additionality) to all sectors (not only transport)[3]
- The **delegated act** related to the **additionality** principle is expected to set rules to have joint investments in electrolysers and renewable capacities.[4]
- The EU **taxonomy**, requiring that emissions from electrolysis shall not exceed 3 kgCO2/kgH2 (i.e. circa 60 gCO2 per kWh_e).
- The **revision of the TEN-E Regulation** and the upcoming Guidelines on Cost-Benefit Analysis of hydrogen and electrolyser projects (and the eligibility criteria for categories (3) and (4) related to sustainability for inclusion into PCI or PMI Union lists).

The development of hydrogen is foreseen to have potentially deep **impacts on many sectors**.
The **hydrogen ecosystem** includes a large number of components and end-uses, some being in competition with direct electrification, others with the use of gases from other origins (e.g. biomethane, natural gas + CCS):

- Industry (ammonia, steel and iron…).
- Residential and tertiary sector (fuel cell CHP).
- Power sector (power to gas / gas to power, storage).
- Hydrogen production (electrolysis competing with SMR, ATR, pyrolysis, etc.).
- Gas infrastructure (blending, repurposing and refurbishment of pipes and storages, new investments…).
- Mobility (H2-vehicules, fuels for maritime and aviation).

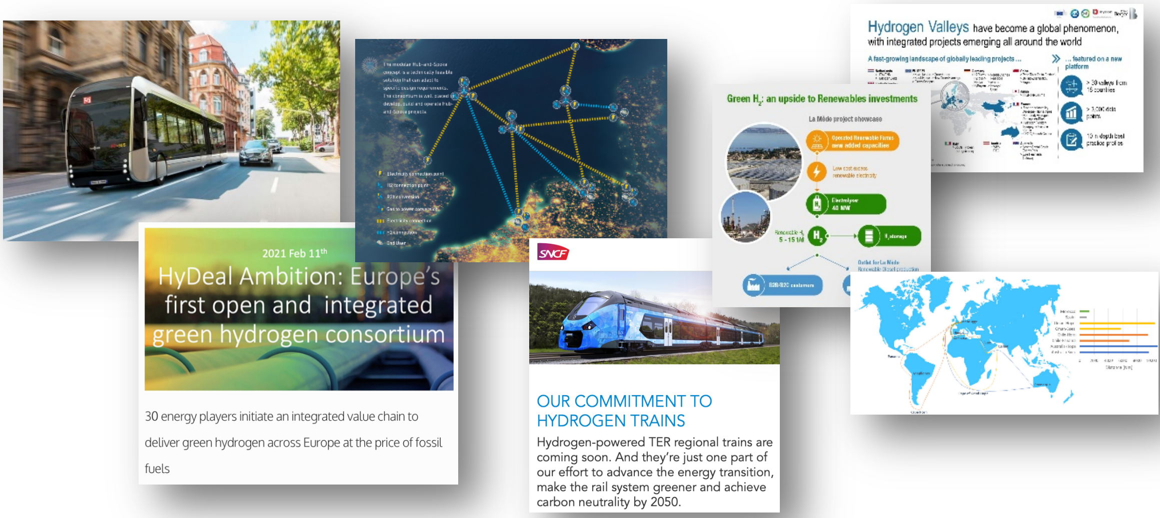
Today we see **pilot projects emerge in all components of the ecosystem**, tackling complex issues such as:

- Regulation (taxes, sustainability assessment of electrolysis…).
- Finance (capital available for pilot projects, what about the massive investments needed to decarbonise the entire economy?).
- Public acceptance, attractiveness of options.
- Economic aspects (learning rates, subsidies…).

[3] https://ec.europa.eu/info/news/commission-presents-renewable-energy-directive-revision-2021-jul-14_en

[4] https://www.euractiv.com/section/energy/opinion/additionality-the-key-to-turn-the-hydrogen-buzz-into-a-renewable-boom/

Many projects are emerging but in a very fragmented way, and with very little common long-term vision.



Methodology

The methodology used relies on two streams:

- A **literature review** of circa 25 recent publications that deal with one or several aspects mentioned in the introductory slides
- **Interviews of around 10+ key experts**. While they have participated in shaping some of the arguments presented today, the views expressed herein are those of the authors only.

The experts we interviewed gave insights and opinions on various aspects of the report. Those interviews helped inform the report but this shall not be considered as a shared vision amongst the different experts. On the contrary, we tried to highlight as much as possible the variety of visions, even if these visions are partially in contradiction. The listed experts should not be considered accountable for parts or the totality of the report.

Name	Company / Institution
Maxime Sagot	Afhypac
David Le Noc	ATEE
Pierre-Laurent Lucille	ENGIE
Guillaume Fournel	CRE
Carole Le Henaff	GIE/Storengy
Cédric Philibert	IFRI
Sylvain le Net	France Chimie

Paul Lucchese	IEA / CEA
Gniewomir Flis	Agora Energiewende
Stijn Carton	European Climate Foundation
Ines Bouacida	IDDRI
Jean-Pierre Goux	Independent expert (ex-Powernext CEO)
Florence Delprat-Jannaud	IFPEN
Daniel Marenne	ENGIE

A 3-perspective study

In order to structure our assessment, we have decided to look at the relevant aspects under **three different perspectives**, each of them having their own SWOT dimensions:

- **SYSTEM-LEVEL** (including economics, sustainability, externalities, value chain, etc.)
- **PROJECT DEVELOPERS** (from infrastructure to manufacturers of appliances via electrolysis)
- **CONSUMERS** (from industry to domestic sector via mobility)

Each theme of our literature review and expert's interview was examined sequentially under those 3 points of view. By doing so, we were able to identify some mismatches of interest and some potential measures to overcome this.

2 Key findings

In the context of deep decarbonisation of our economies, the consensus tends to make hydrogen emerge as a necessary brick of the energy strategy. Behind the current enthusiasm around hydrogen, the reality could be in fact much more complex and nuanced. If some people see H2 as "the oil of the zero-carbon economy", others predict much more restricted perspectives for this gas.

On a **systemic point of view**, hydrogen is very interesting solution that could solve some of the most complex problems of a carbon free energy system.

Among the values for the system that could bring hydrogen, we identified the following three as the most important ones:

- H2 can be the key to decarbonise hard-to-abate emissions
- H2 can provide the missing technology for energy storage
- H2 can be a cost-effective way to transport large amounts of energy

On the other hand, we identified some hurdles that are clearly mitigating the prospects for hydrogen:

- The depth of the future H2 market is heavily debated with very different visions. For some experts, H2 is likely to remain a niche market compared to electrification.
- The value chain efficiency of hydrogen is very low
- The transition costs are expected to be high
- H2 growth relies on technological bets
- H2 is a hazardous gas that is complicated to handle, especially besides industrial applications.

In addition, H2 development raises complex questions that need to be answered when considering its systemic value.

No consensus exists on the level of required infrastructure for H2. Hence what will the H2 infrastructure look like? Will the H2 system be made of local distributed systems around clusters or of a large European infrastructure?

In order to associate a positive systemic impact of H2 usage to reach net zero target, the true CO2 carbon impact of H2 production must be carefully examined. Yet, even electrolytic H2 consuming renewable electricity (the so called green H2) can in fact have a non-virtuous impact depending on the configurations. Indeed, the whole energy system must be taken into account and especially the potential lack of renewable electricity consumption for power usages resulting from the consumption for H2 production purposes.

Finally, the risks to have "game changer elements" emerging and changing the whole energy landscape must not be underestimated (long distance H2 trading, deflation of the H2 bubble, large development of Small Modular Reactors, etc.)

The development of a « hydrogen economy » can represent very interesting opportunities for **project developers**. However, the risks remain high and the gain expectations are very unclear. Moreover, few of those opportunities are real “game changers” triggered by the new usage of hydrogen, as they do not really enable new goods and services to appear or reduce the cost of existing goods and services. Most of those opportunities seem relevant only in a context of deep decarbonisation.

For the **consumers**, hydrogen usage proved very little advantages compared to alternative solutions, besides the opportunity to decarbonise the final usage. On the contrary, the drawbacks of using hydrogen, and above all the cost premium are very important.

This lack of alignment of interest between the 3 studied perspectives suggest that the development of H2 is very unlikely to emerge by itself, even if its value for the system is clear. Some kind of support will be required to rape the hydrogen fruits in the future.

What is Hydrogen?

The so called “Hydrogen” refers to the chemical molecule of di-hydrogen H2, composed of two atoms of hydrogen. At normal conditions of temperature and pressure, hydrogen is a gas. It can nevertheless be turned into a liquid at very low temperature and high pressure. Liquid hydrogen is very difficult to produce but already has some use cases for example in rocket engines. Hydrogen is a very reactive chemicals that can liberate a lot of energy, that is why its usage is more and more studied for the energy system in addition to its usage as a chemical feedstock.

Usages of hydrogen

There are two main ways to use hydrogen for energy supply. The first way is by **direct combustion** (with oxygen), the energy liberated is on the form of heat that can be exploited in engines. The second way is by the usage of **fuel cells** that transform the chemical energy into both electrical energy and heat. Hydrogen can also be used as a **feedstock** of chemical reaction that is used to synthetise more complex chemical elements. This capacity to transform H2 into other chemical components is an opportunity to transport hydrogen and energy under other forms like ammonia (NH3).

Production of hydrogen

If the atom of hydrogen is the simplest and most common element in the universe, there are very few natural sources of hydrogen on Earth that could be exploited. As a result, **hydrogen is not a source of primary energy** such as oil, natural gas, wind, solar or nuclear fuels. All the hydrogen that we want to use must be synthetised. Different ways of production exist and many others are explored by researchers. They use different initial energy sources:

- With **natural gas**: it is the most common way to produce hydrogen today. The two main processes are steam methane reforming (SMR) and autothermal reforming (ATR).
- With fossil fuels like **coal** by gasification processes.
- With **electricity** by electrolysis. Electricity is not an energy source and needs to be produced. The energy source in that case is the energy source that was used to produce this electricity (wind, solar, hydro, nuclear, gas, coal, …). The energy source that is used for electrolysis has profound impacts on the sustainability of hydrogen production.
- Other processes exist and are under development like pyrolysis, or gasification of biomass.

A hydrogen economy is not fundamentally clean or carbon free, it mostly depends on the energy source that is used to synthetise the hydrogen. Some of the most common production means are in fact highly carbon intensive (hydrogen synthetised from coal or methane). Even the electrolytic hydrogen is just as clean as the electricity that was used to produce it (see deep dive on this topic in Section 3.1.3.6).

One gas, many different colours

The industry and energy experts have developed a **colour code** to name hydrogen depending on the process used to produce it. All those hydrogens types are completely equivalent in terms of chemicals and physical proprieties and nothing can distinguish one from another except the way it was produced. For concisely and simplicity reasons, we will use some of those colour appellations, even though those distinctions fail to grasp all the nuances. In this report we will mainly use the followings:

- **Grey H2:** synthetised with reforming of methane.
- **Blue H2:** synthetised with reforming of methane to which is added a carbon capture and storage system.
- **Green H2:** synthetised with the electrolysis of electricity that was produced with green energy (solar, wind or hydro). Electrolytic H2 produced with nuclear based energy is often excluded form green H2.
- **H2 from the grid:** synthetised with the electrolysis of electricity that was directly consumed on the power grid.

Key figures about hydrogen

In literature, H2 is either estimated in masse unit (mostly in tons) or in energy units (mostly MWh LHV) by reference to its calorific value. The following equivalence can be kept in mind:

3 SWOT analysis

3.1 System point of view

In this section, we will analyse the strengths and weaknesses of hydrogen on the point of view of the system.

3.1.1 SWOT results

STRENGTHS

Main elements

- H2 can be the key to decarbonise some hard to abate emissions
- H2 can provide the missing technology for energy storage
- H2 can be a cost-effective way to transport large amounts of energy

Additional elements

- Carbon neutral H2 production can be performed with several well-known processes
- H2 can be a diplomatic asset
- H2 can be solution against air pollution
- H2 enable to keep similar energy habits as today
- H2 can serve as basis for the synthesis of several other carbon neutral fuels

WEAKNESSES

Main elements

- H2 growth expectation could be less than expected
- H2 value chain's efficiency is low compared to its main competitors
- Transition cost are very high all across the value chain
- H2 can be complicated and do handle in safety conditions

Additional elements

- The real systemic carbon impact of green H2 is not so clear
- Bleu H2 remains a highly controversial subject

OPPORTUNITIES

- H2 infrastructure could be the key for the development of the sector
- The public support and public momentum are strong
- Blue H2 is a clear opportunity to start up the H2 sector at limited cost
- Taxation could boost H2 adoption

THREATS

- The switch to H2 in the industry can have important macro-economic impacts
- Risk of badly calibrated regulation
- Some game changers events could disrupt the current expectations for the hydrogen sector
- Misallocation of capital

3.1.2 H2 is often seen as a valuable asset for the future energy system

Today, most of the long-term prospective scenarios agree that hydrogen is expected to play a role in the future: European Commission scenarios, ENTSOs TYNDP, PAC scenario, …

For the system, **3 main strengths** are often associated to the development of hydrogen:

- H2 can be the key to decarbonise hard-to-abate emissions
- H2 can provide the missing technology for energy storage
- H2 can be a cost-effective way to transport large amounts of energy

3.1.2.1 First strength: decarbonize the hard-to-abate sectors

A large consensus among the experts and stakeholders indicates that one of the biggest values of hydrogen in a carbon neutral energy system is **its ability to decarbonate "hard-to-abate emissions"**. This term often refers to the current CO2 emissions for which carbon-free alternatives are very expensive or sometimes not even available. Generally, the carbon free alternative in question is direct electrification but, in many applications, it can be very complicated to put in place and can be prohibitively expensive. For distance transportation for example, the energy density required to be economically viable often dismisses the electrical solution (with battery storage), to the profit of liquid or compressed gases.

The first reservoir of future demand: decarbonisation of current feedstock usages

Today, hydrogen is used for some very specific applications as a feedstock: in 2019, the global consumption of H2 (both under pure and mixed form) represented 115 MtH2 or 3840 TWh[5]. The gas is used for its chemical characteristics (feedstock usage) and not as an energy vector. Using carbon free hydrogen as feedstock in thoses sectors is the first usage to take into account. The main feedstock usages are presented in the figure below [Figure 1]:

[5] (IEA, 2019)

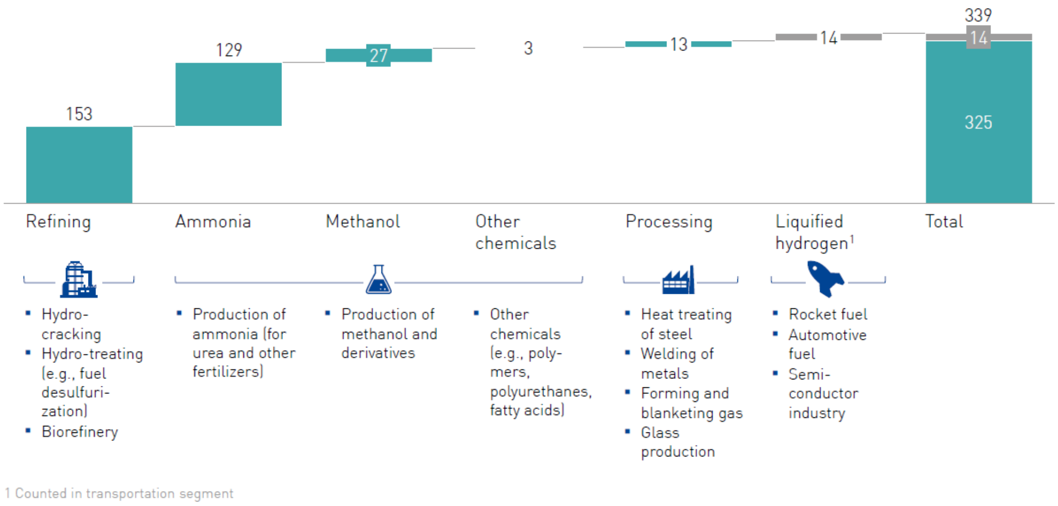


Figure 1: Total hydrogen use in the EU in TWh[6]

New potential energy usages in a context of deep decarbonisation

In addition to the usages listed above, many publications and experts identify hydrogen as a promising energy vector for several applications where electrification seems out of reach from an economic and/or technical point of view. The followings usages are often quoted:

- **Some industrial processes**
  - Steel industry
  - Cement
  - Chemicals industry – as energy carrier
  - High value chemicals
- **Transport applications**
  - Maritime transport
  - Heavy duty transport
  - Rail and Aviation
- **Decarbonisation of the power sector**
  - Storage for the power grid
  - Backup solutions

If some of the applications listed above were to be switched to H2, the prospects for hydrogen would completely change. For example, the prospective committee of the French energy regulator[7] estimated that the market share of H2 for iron production could be in France 500 ktH2, which is approximately the current H2 production of France (H2 co-produced put apparat).

[6] (Fuels Cells and Hydrogen – Joint Undertaking (FCH-JU), 2019)
[7] (Comité de prospective de la CRE, 2021)

However, there is no consensus on the future H2 demand that could fall under those so called "hard to abate emissions". Indeed, more and more alternative to H2 are being explored and the real market share corresponding to the H2 that "will be required anyways to reach carbon neutrality" is still highly speculative.

In the study led by Agora Energiewende and Afry called *No-regret hydrogen - Charting early steps for H_2 infrastructure in Europe*[8], the authors focused on the « no regrets » hydrogen consumptions and considered only the industrial usages of H2. They found out that H2 consumption in Europe could reach 270 TWh in 2030, only slightly more than today's demand [Figure 2]. Many other estimations found out very different results with much higher projected demands [Figure 3].

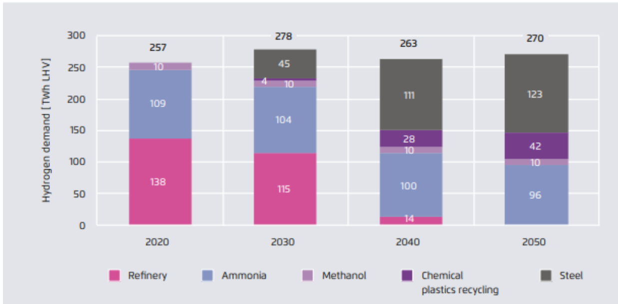


Figure 2: Hydrogen demand projection in Agoras's study[1]

The EU-LTS 1.5 Tech scenario[9] foresees a much larger usage of H2: hydrogen is used in the industry, the power generation, households heating and also as a feedstock to synthetise e-fuels. The study estimates a H2 demand in 2050 of up to 896 TWh to which must be added an additional 523 TWh of e-liquids.

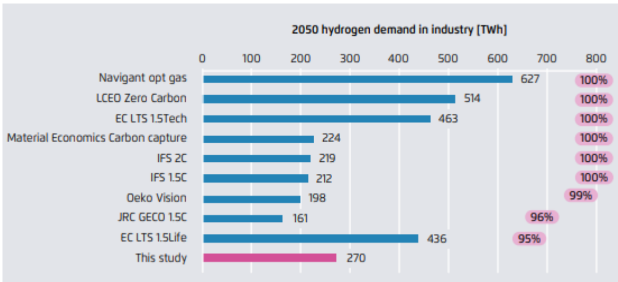


Figure 3: Hydrogen demand in industry in different studies. "This study" refers to Agoras's study Error! Bookmark

The scale of H2 usages developed recently by Liberich Associates is an attempt to classify all the potential H2 usages in terms of desirability of the system. At the top of the scale, we find what are considers the "unavoidable" usages for which H2 is seen as indispensable (fertilizers, methanol…) and at the bottom the "uncompetitive" usages for which the H2 solutions seem today not in line with the available alternatives, even in a carbon neutrality context. This approach has several drawbacks, notably the fact that it only focuses on efficiency and not in total cost for the system, but it remains a good tool to clarify the prospects of H2 usages.

[8] (Agora Energiewende - Afry, 2021)
[9] (European Commission, 2018)

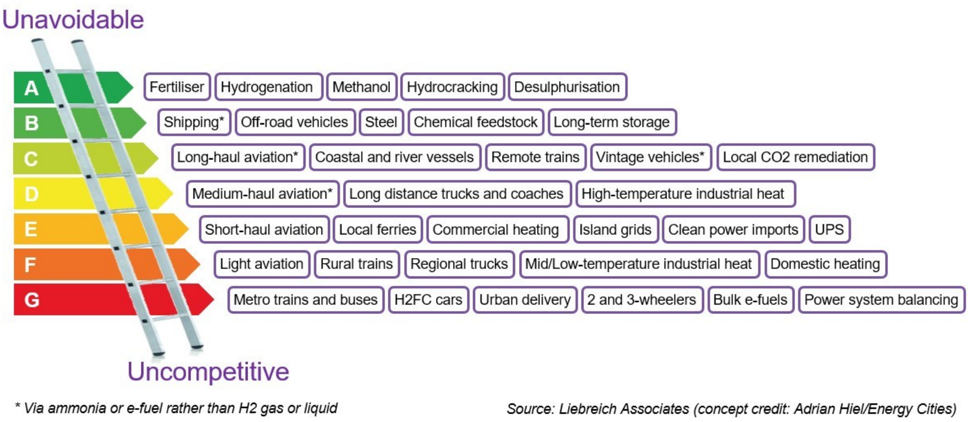


Figure 4: Scale of hydrogen usages, Liebreich Associates

Hydrogen can be therefore a very important piece to decarbonise the energy system by tackling the carbon emissions of sectors that are very complicated to electrify or to decarbonize by other means. Hydrogen is a power way to abate the "hard to abate emissions". Nevertheless, the number of those "hard to abate sectors" is debated.

3.1.2.2 2nd strength: A potential solution for the growing energy flexibility problem.

What is the problem to address?

The energy transition (mainly the electrification of usages) combined with the growing share of intermittent power production in the electricity mix make it more and more difficult to match power production and demand at all time. The need for additional sources of flexibility for the power system appears on several time scales, from infra-hourly to multi-annual, and H2 systems could play a role to help meet these flexibility needs.

Many studies[10][11][12] and experts identify mid-term power flexibility as a missing element to the deep decarbonisation of the power sector while ensuring a good security of supply at reasonable costs. The question that needs to be answered can be formulated as follow:

[10] (NREL, 2019)
[11] (Fuels Cells and Hydrogen – Joint Undertaking (FCH-JU), 2019)
[12] (European Comission, 2020)

“How should the power system react to a long period (typically 2 weeks) of windless cold?”

These so-called “Dunkelflaute” events are already very stressing for the power system and the perspective to rely more on more on wind and solar raises legitim concerns. Today those events are managed with the flexibility solutions that exist in many countries: gas fired power plants, coal plants, lignite plants, nuclear, hydro, interconnection with neighbouring countries… The rise of solar and wind in the European electricity mix will result in the under usage of the other power production facilities and little by the little the closing of the least efficient ones, most of which being carbon intensive flexible productions. Coal and natural gas phase-out strategies are also strongly reducing the installed capacity of flexible production assets. Nevertheless, it remains debated to what extent and how we can replace those flexible productions with intermittent carbon free production at reasonable costs and still match security of supply requirements.

H2, a solution for growing power flexibility needs

Cost benefit analyses have been carried on in multiple studies[13] and have concluded in the **necessity of additional short term and midterm flexibility solutions**. The system can already provide some flexibility without carbon intensive plants by using the interconnections between countries and for some countries the existing hydro and nuclear assets. Those solutions will be largely insufficient at their current capacities in a future with more power demand, more renewable solutions and less carbon intensive generations. Additional investments in flexible assets will be required. Figure 6 from FCH-JU hydrogen roadmap compares fuel cells and batteries as flexibility solutions at different time scales and their respective advantages and drawbacks, as the storage duration needs is one key to assess the appropriate technology.

The **short-term flexibility** need is expected to rise significantly with the development of solar production and the electrification of heat provision. However, this growth market is often seen as the ideal **business case for battery storage solutions rather than H2 systems.** The consensus is that hydrogen solutions will struggle to extract value in this field given the cost difference with batteries and the flexibility limitations of current hydrogen fuel cell solutions. In addition to the short-term flexibility, battery storages can also provide numerous ancillary services (which is the current business case for those assets). H2

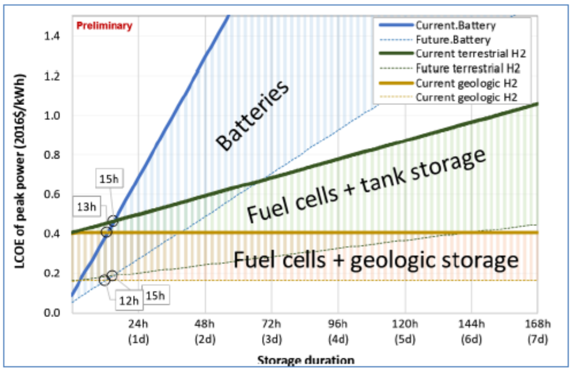


Figure 5: Economic preference benchmark current & future hydrogen and batteries (NREL, 2019)

[13] (European Comission, 2020)

solutions are much more limited in this field. However, the electrolysis processes used for the production of green H2 is expected to have some degrees of short-term flexibilities depending on the technologies.

The **mid-term flexibility**, is the current business case of hydro storages. Nevertheless, it is more and more difficult to build additional capacities, both for costs and for public acceptance reasons. Moreover, the needs for mid-term flexibility (a few hours to a few days) will be particularly important with the rising share of wind and solar productions. Many are looking for a new solution to ramp-up flexibility capacities and **hydrogen has been identified as one very promising possible solution**. Indeed, electrolytic hydrogen could be the ideal solution to “store electricity” through “power to H2 to power” loop. Figure 5 shows that beyond 10 to 15 hours, batteries are expected to no-longer be competitive with hydrogen storage solutions.

Storage of electricity with H2 requires nevertheless some specific characteristics such as a very high H2 power production capacity to transform the hydrogen back to electricity (often at rather low efficiency), and large H2 storages (which is more complicated for H2 than natural gas).

If the storage side of the equation seems reachable at reasonable costs for a mid-term storage, the production capacity side raises some concerns. Indeed, the fuel cells to do the backward loop (hydrogen to power) are very expensive and would only function for a limit number of hours per year. Another technical solution could be to use this hydrogen in new OCGT turbines specifically designed to accept hydrogen. **Using a capital-intensive technology for a security of supply application that is designed to be used a very limited number of hours is counter-intuitive**.

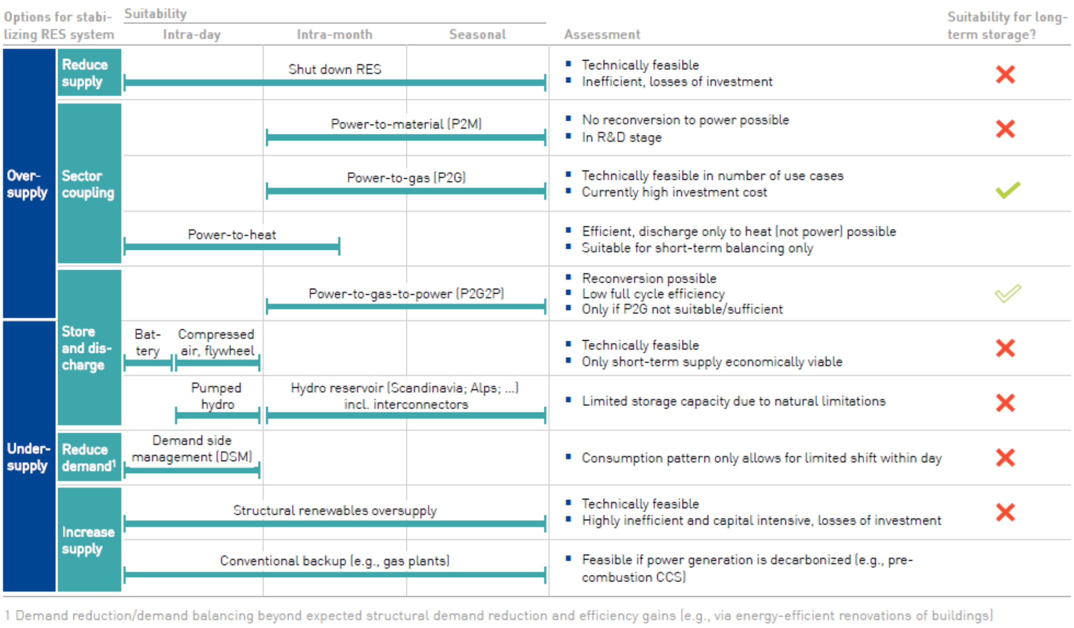


Figure 6: Comparison of technologies for different flexibility needs.
In its hydrogen roadmap[1] the FCH-JU proposed this comparison of available technologies to serve different flexibility needs. Power to gas is a valuable solution to cope with oversupply. Power to gas to power is seen as one of the only solutions to deal with intra-month and seasonal undersupply at reasonable costs to complete the hydro reservoirs and conventional carbon intensive back-ups. Nevertheless, they acknowledge that this solution suffers from low full cycle efficiency. (Fuels Cells and Hydrogen – Joint Undertaking (FCH-JU), 2019)

Hydrogen is one of the only options that could solve the midterm flexibility needs required by a deeply decarbonised power system relying on intermittent energy sources like solar and wind. However, the investment costs are expected to be very high which is counter intuitive for a project designed to function some hours in the year.

Potential use case for long-term storage?

As far as long-term storage is concerned, no consensus emerges. Today, the long-term storage in the energy sector is the realm of natural gas and many see H2 as its carbon neutral substitute. However, direct comparisons between the current usage of natural and the future expected usage of hydrogen should be done with caution. The real need of long-term flexibility for the power sector will depend on the evolution of **three factors** that we see today:

- **Electrification of the demand** that leads to a transfer of thermo sensitivity from gas to the power sector. The massification of heat pumps even in areas where the winter is cold can also induce an even more "peaky" power load curve, as heat pumps have decreasing efficiencies with decreasing temperature. A sharper load curve, induces more flexibility.
- **Growing energy efficiency** relying on two main factors:
  - Energy insulation of houses (in new building and old constructions) to reduce the need for heating.
  - The energy efficiency of heating devices: classical Joule-effect power heating devices being replaced by heat pumps with high coefficients of performance.
- **Seasonal repartition** of the energy supply. Since wind load factors are higher in winter than in summer, an energy system with large wind capacities could have fewer net power demand (power demand to which one subtracts the variable renewable production) in winter.

Besides the "electricity storage" usage, the business case for long term hydrogen storage depends on the dynamics of both the hydrogen demand and the hydrogen supply.

For the supply side, it will depend on the production business model of hydrogen (electricity provided by solar, wind, hydro, diversified RES portfolio, nuclear, direct network consumption; flat production profile or price-responsible management; etc.). For the demand side, it will mostly depend on the sector in which H2 is used. Industrial demand is expected to be rather flat across the year whereases heating demand is expected to be thermosensitive. Hydrogen storages are probably required to match a variable supply of H2 with a steady H2 demand, but their role of corner stone of seasonal storage is very uncertain.

On the technical part, all the problems encounter for mid-term storage are exacerbated with long term storage, with larger storage capacities generally being required. Moreover, the development of hydrogen network is a prerequisite to the usage of centralized storage capacities.

Comparison between gas and hydrogen

In order to have a clearer vision on how gas and hydrogen storages could be compared, we identified some of the explicative factors of the need for storage and we compare the two gases for each of these factors.

	Natural Gas	Hydrogen
Production geography	Mostly imported	Produced locally (most probable) Some international imports could be envisaged
Production flexibility/variability	Mostly inflexible	Flexible operations of the electrolysis plant Variability of the RES production
Storage characteristics	Easy to store in large quantities	Can probably be stored in large quantities but research is still ongoing for some types of cavities
Storage integration in the network	Storages are completely integrated to the gas network	No large-scale cross-border network exists as of yet
Final demand of the fuel	Extremely thermosensitive (driven by heating)	Mostly non thermosensitive (driven by the industry and part of the transport sector)
X to power need	Gas to Power is thermosensitive for the moment. Electrification could increase this thermo-sensitivity whereas energy efficiency and renovation could reduce it. Both Gas to Power and Hydrogen to power have a capacity value.	

As the role of tomorrow's hydrogen is expected to be very different from the one of today's natural gas, the characteristics of the hydrogen storages could be very different from what we are used to today with natural gas.

3.1.2.3 3rd strength: cost effective way to transport green energy

Of course, H2 will never be as convenient as oil or natural gas to transport large amounts of energy across long distances. Nevertheless, these vectors which are very efficient to transport energy have the big drawback to emit large amounts of CO2 when used. Most of the long-term scenarios agree on the necessity to massively develop renewable energies and renewable electricity is expected to get the largest market share. In this context, **H2 is seen as a potential energy vector of "renewable electricity production"**, that could be transported in the form of gas rather than electricity.

Very little consensus exists amongst experts and publication on the actual cost of building a large-scale hydrogen infrastructure. However, experts agree on two things:

- Transporting energy through H2 is cheaper than through electricity
- Repurposing current gas infrastructure is cheaper than building new H2 infrastructure[14].

This argument is investigated by a number of recent publications. In their *Infrastructure outlook 2050*[15], Gasunie and TenneT found out that the installation of P2G facilities (Power to Gas) next to RES production centres (and especially next to wind production) is key to prevent constraints (and investments) on the power network:

> *"Converting renewable energy to hydrogen at locations close to the renewable production facilities will relieve bottlenecks in the electricity infrastructure, without causing problems for the gas infrastructure. This means that the location of P2G installations is crucial for the energy flows in the system and the amount of renewable energy that can be collected using hydrogen as a carrier."*

An H2 infrastructure in the form of what is often called a "backbone" could be a cost-effective way to rationalise the different energy requirements inside Europe. The need for rationalisation is expected to grow as renewable productions and demand patterns are very different across Europe.

Moreover, long distance H2 transport can be a solution to import **cheap green energy from outside Europe** where renewable production is more cost effective than it is within Europe. We provide more details on this topic in Section 4.2.

3.1.2.4 Other strengths of Hydrogen vector for the system

H2 processes are well known and new processes are in development

Hydrogen production is a well-known process and many industrial facilities are already producing it in large quantities (mostly with natural gas in Europe). These already existing production capacities are

[14] Table 1
[15] (Gasunie, TenneT, 2020)

key assets for the future productions of hydrogen. Blue H2 is undisputedly the current cheapest solution to produce low-carbon hydrogen by adapting the existing SMR and ATR plants to enable capture transport and storage of CO2. Moreover, the switch from grey hydrogen to blue hydrogen can be automatically driven an appropriate carbon price signal, without any public support, without any capital destruction, and without changing the industrial consumption habits. Nevertheless, this solution is warmly debated and many experts defend the idea to avoid a first "blue H2 step" and to directly jump to green H2. This issue will be discussed in more details in Section 4.1.

Many other production technologies are being studied at different maturity levels. The Figure 7 details some of the most promising production pathways.

Exhibit 1.6

Multiple potential clean hydrogen production pathways; however, two pathways likely to dominate hydrogen scale up in coming decade

Clean H_2 production pathways: — Priority production pathways: Green, Blue — See technical annex for further information

H_2 Source input	Additional inputs	Process	CCS required? (*neg. emissions)	Reason for prioritization / de-prioritization
Natural Gas	Power¹ + water	Steam methane reforming (SMR)	+ CCS	Commercially available and deployed in pilots/few commercial plants (<5); commonly employed with only 60 % capture rate today; higher capture rates more expensive
Natural Gas	Power¹ (heat produced in reformer) + water	Autothermal reforming (ATR)	+ CCS	Commercially available and deployed in pilots; typically larger plant scale, high CO_2 recovery rates & lower CCS costs due to concentrated CO_2
Natural Gas	Power¹ + oxygen (no combustion)	Chemical looping	+ CCS	Low TRL (~100kW); no investment from industry
Natural Gas	Power¹ + oxygen	Partial oxidation (POX)	+ CCS	Similar to ATR, commercially available, high CO_2 capture & lower CCS costs, more flexible on feedstock, lower purity hydrogen product
Natural Gas	Power¹ (no oxygen)	Pyrolysis (methane splitting)		Some promising technology at lab/pilot scale; lower TRL; no CO_2 emissions during process; option to sell by-product 'carbon-black'
Liquid hydro-carbons	Power¹ + oxygen	Partial oxidation	+ CCS	Upgrading of residual refinery hydrocarbons to hydrogen. Overall smaller volumes with declining role towards mid-century
Coal	Power¹ + oxygen + water (partial combustion)	Coal gasification	+ CCS	Lower process efficiency than SMR; higher carbon emissions per kg hydrogen therefore CCS more expensive
Biomass	Power (no oxygen)	Pyrolysis	+ CCS*	Constrained by limited sustainable, low-lifecycle carbon bio-resources
Biomass	Power + oxygen + water (partial combustion)	Biomass gasification	+ CCS*	Complex processing, more expensive than alternative routes (especially given high biomass collection costs), with low TRL
Biomass	Microorganisms (no oxygen)	Bio-chemical		Biomass has lowest hydrogen to carbon ratio from all feedstocks, hence highest CO_2/H_2 emissions
Biogas	Power + water	Biomethane reforming	+ CCS*	However combined with CCS could create "negative emissions" – may have a long-term local role where sustainable biomass available
Water	Power	Electrolysis		Declining costs of renewable power, and equipment costs decline with scale - 'zero-carbon hydrogen' feasible
Water	Nuclear power	Thermochemical water splitting		Low TRL (lab-scale), large advancements in tech required, high cost uncertainty
Water	Solar power	Solar-chemical water splitting		Low TRL (lab-scale), large advancements in tech required, high cost uncertainty

NOTE: ¹ Power input depends on plant design and CO_2 capture. Power often provided through combustion of fossil input.

Figure 7: Clean hydrogen production pathways, (Energy Transition Commission, 2021)

> Hydrogen is a well-known fuel and many processes exist to produce it. New production technologies are under study. Electrolysers are already used for H2 production and the technologies are rapidly improving.

H2 is often seen as an economic and diplomatic asset

We can clearly identify today a **political momentum on hydrogen-related subjects**, driven by the idea that the emerging hydrogen economy can help energize the industrial tissue in many countries like France. If hydrogen is to become the new oil, everyone wants its **hydrogen major**.

On a local level, the hydrogen economy is seen as a powerful way to attract investments and develop local labour forces. The French agency ADEME estimated in its study *Hydrogène : analyse des potentiels industriels et économiques en France*[16] that between 58.000 and 107.000 new jobs could be created in France in the hydrogen sector.

As hydrogen can be produced locally as long as there is supply of low-carbon electricity, many countries see hydrogen as an opportunity to improve their **energy independence**. This can have several purposes:

- **Improve the foreign trade balance**. Oil and gas imports are currently important components of the foreign trade balance in most European countries. The hydrogen economy replacing fossil fuels is therefore very appealing.
- Improve their **political independence** toward energy suppliers.

This industrial opportunity does not only concern the production of hydrogen but **also the production of important technologies of the hydrogen value chain** (electrolysers, H2 storage assets, fuel cells, etc.). It is clear that many European countries like France or Germany do not want to see this industrial opportunity fly away like the solar industry did to China around a decade ago.

> The hydrogen economy can have a very positive impact on local industries and labour market. It is also an opportunity to ensure a kind of energy independence and reduced the required importation of

The local production of green hydrogen requires large-scale investments in RES capacity. If these assets (namely solar panels and wind turbines) are mostly produced abroad, the import of those technology will have an impact on the trade balance**. It is more accurate to talk about a relative transfer of energy dependence rather than energy independence** in that case.

The development of a hydrogen economy comes with a risk of mismatch between the interests of different European countries. This problem has appeared for example between France and Germany with two different visions on the role of and the production of hydrogen. In particular, Germany focuses on the technology side of the hydrogen economy and plans to import cheap H2 to supply its needs when H2 strategies in France mainly focus on local production of H2. This is exacerbated by the desire of industrial countries to have their own "national champions".

[16] (ADEME, 2019)

In this context of mismatch of interest, a common European strategy could play an important rationalisation role. This could prevent a patchwork of incompatible plans between countries and help to the creation of industrial synergies.

The switch of dependence to some critical technologies (solar, wind) and countries shall not be underestimated. It can also induce a mismatch of interests in EU. Collaboration in the EU is seen as important to deal with this issue.

H2 is a solution against air pollution in the very short term.

The usage of H2 instead of fossil fuels can already have a big impact in polluted areas. Indeed, its usage in fuel cells release no pollution (contrary to its usage as a combustible that releases large amounts of NOx). The deployment of hydrogen in transport can be seen as a solution to fight against the air pollution problems of dense cities. Korea for examples planned to develop H2 mobility with an objective of 3 million FCEVs (fuel cells electric vehicles) by 2040 in order to fight against air pollution and boost economic growth[17]. The IEA sates that in India:" *The Supreme Court asked Delhi to explore use of fuel cell buses in the city to counter air pollution, and the government published an INR 60 million call for research proposals on hydrogen and fuel cells."*[18]

Hydrogen usage instead of liquid fuels, regardless of how H2 is produced, is very efficient against air pollution which is a very important issue in many cities. It should be noted that direct combustion of H2 still emits NOx. Air pollution is for many cities a strong argument to push the development of fuel cell vehicles

H2 enable to keep the same energy usage habits as today

One of the key strengths (and potential threat as we shall see later) of hydrogen is its ability to provide "similar energy usages and habits as before the transition", without the inconvenience of carbon emissions. The most striking proof of it is the common saying that "**hydrogen is the new oil**". Indeed, oil has deeply shaped our economies and societies, and is going to be challenging to replace to provide the same level of services. The possibility to keep the current system, only replacing oil and gas with hydrogen is hence a very attractive and reassuring idea.

A few examples support this idea:

[17] www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_seq_n=161262&bbs_cd_n=81.
[18] (IEA, 2019)

- There is no disruption needed in a switch from using natural gas to using hydrogen for heating purposes. Many European cities have already gone through an energy vector switch when natural gas replaced local coal-based town gas.
- H2 mobility has more or less the same characteristics than fossil fuel mobility with less efficiency and much more costs at the moment. On the other hand, the alternative solution of electric mobility requires a change in our mobility habits:
  - The time spend to refuel a car with conventional fuel and hydrogen are very similar, however it takes some hours to recharge an electric car in the absence of supercharging infrastructure.
  - It is very easy to conceptualise H2 stations in highway stops, but being dependant on the availability of an electric charging station in the highway is less reassuring, all the more if we consider holidays overcrowded departures.

Hydrogen provides for some usages the promise of a smooth transition without major disruption of habits and model.

H2 is a basis for plenty of new fuels

The chemistry of hydrogen enables the synthesis of many other hydrogen-based chemicals that can play a role in the energy system. The most promising solution is the usage of hydrogen to synthetise ammonia (NH3) that can then be used for energy usage (in addition to its feedstock usages) and that is quite simple to handle and store, especially when compared to hydrogen itself. The other solution that is often proposed is to use hydrogen and CO2 to synthesis chemicals more or less identical to fossil fuels using Fischer Tropscht or Haber Bosch processes. We talk here of **e-gases, e-fuels or synfuels**. Those e-fuels are almost identical to fossil fuels from a chemical perspective, and therefore have all the advantages that made the hegemony of oil-based fuels (energy density, liquid state, stability, storage, transport,). The FCH-JU stated in their Hydrogen Roadmap for Europe [19]:

> *“Synfuels have two main advantages: they achieve the energy density of current fuels and they can be used as a “drop in” to the current fuel pool.”*

In some prospective scenarios, e-fuels represent a high share of the final energy consumption (12,6% of the total final energy consumption in the 1.5 TECH scenario of the EU LTS[20] with up to 1000 TWh). This solution also provides a very interesting outlet to CO2 that is captured elsewhere. However, in

[19] (Fuels Cells and Hydrogen – Joint Undertaking (FCH-JU), 2019)
[20] (European Commission, 2018)

many scenarios, e-fuels do not play any role (in the baseline scenario of the EU LTS that does not reach carbon neutrality in 2050, e-fuels are not used at all in 2050[21])

Hydrogen is a very versatile chemical and can be used to produce a whole set of other fuels that can also play an important role in the energy system.

3.1.3 But many hurdles may mitigate the current hype

H2 is far from bringing consensus among energy experts and stakeholders. In this section we explore some of the elements that are subject to debate or to controversy and that could change the vision we have on hydrogen role.

3.1.3.1 Is H2 really a growth market?

Currently, H2 is mostly used in 4 sectors[22]:

- Oil refining (33%)
- Ammonia (27%)
- Methanol production (11%)
- Steel production via direct reduction of iron ore (3%)

Hydrogen has clearly been a growth market in the past few years as shown in the Figure 8. But today, many experts question the prospects of the current demand sectors. Indeed, carbon neutral objectives will require to consume as few fossil-based products as possible, reducing the growth prospects of H2 in oil refinery. Ammonia is used to produced fertilisers, but a growing trend in western countries is to reduce the consumption of fertilizer products and to focus on natural methods and organic products. Some claim that this trend could jeopardize the prospects of ammonia in Europe.

[21] (European Commission, 2018)
[22] (IEA, 2019)

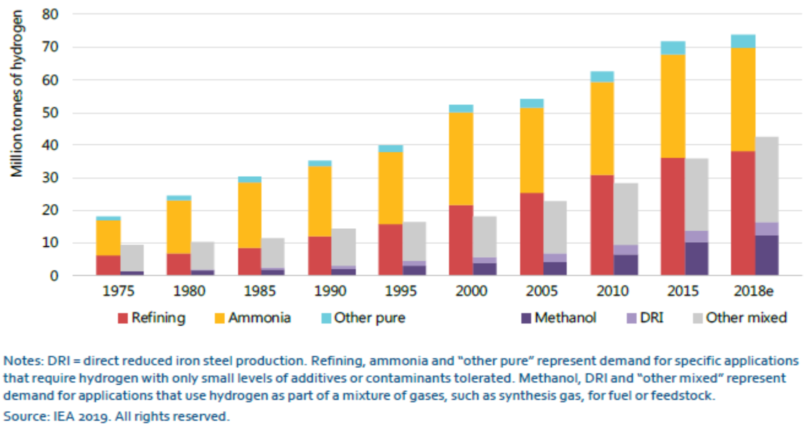


Figure 8:Global annual demand for hydrogen since 1975, (IEA, 2019)

The role of H2 to decarbonize hard-to-abate emissions is unclear

Electrification

The latest progress in electrification of industrial processes suggests that things that once were considered out of reach for electricity can be considered now as potentially viable and even cost competitive. For example, much progress was made in the high temperature electric furnaces. More and more studies suggest that the hard to abate emissions that cannot be electrified easily could be much less than it was previously assumed [Figure 9]. In the study ***No-regret hydrogen – Charting early steps for H2 infrastructure in Europe***[23], Agora Energiewende states:

"Even for higher temperatures, a range of power-to-heat options can be more energy-efficient than hydrogen and should be considered first"

[23] (Agora Energiewende - Afry, 2021)

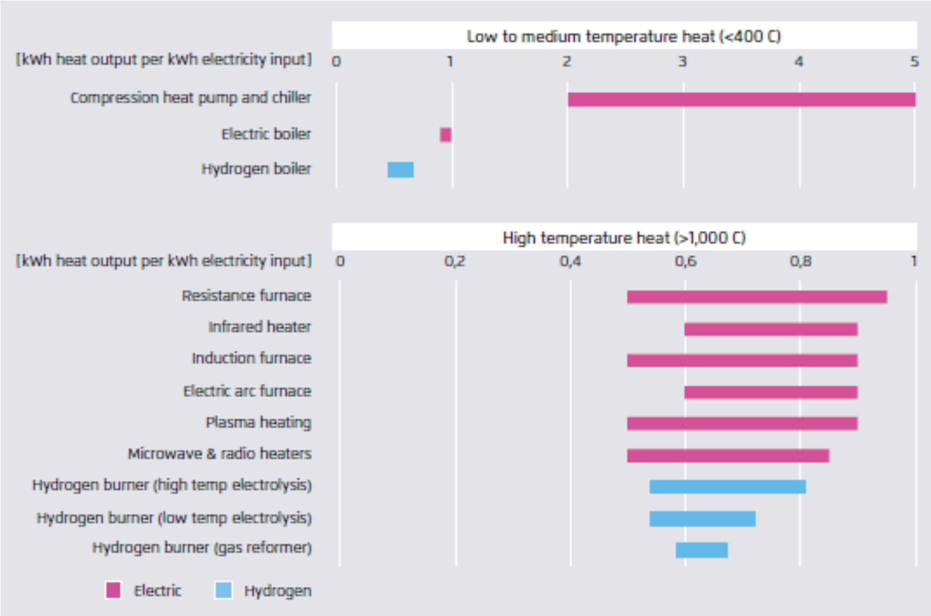


Figure 9 : Performance factors of power-to-heat technologies vs. heat from burning hydrogen derived from electrolysis (Agora Energiewende - Afry, 2021)

Competition from alternative fuels

Other fuels can play a role in the sectors that are often listed in the “hard to abate emissions” sectors. Biofuels for example have already proven that they are viable energy sources for transport even though some controversies are related to their sustainability. Biomethane injection into the gas grid is also a growing source of carbon neutral energy that can help decarbonise sectors with only very little adaptation cost for the system unlike the costly adaptation to switch from a fossil fuel technology to a new hydrogen technology. The usages of those **other carbon-neutral fuels are therefore direct competitors to hydrogen**, reducing even more the prospects of its usage in the hard to abate sectors.

Other solutions

Finally, other solutions can help reach a carbon-neutral energy system without even stopping the usage of fossil fuels. We can quote two well-known solutions:

- Carbon capture and storage of emissions from industries. These technologies are expected to develop a lot, especially if blue hydrogen is massively adopted. Moreover, this solution will also be needed for non-energy CO2 emissions in industrial processes (ex: cement production).
- Carbon compensation of emissions with investments in carbon wells can remain a solution for the very last emissions that would require too massive costs to be switched to e.g. hydrogen.

No certainty emerges today about the real depth of hydrogen needed for the hard to abate sectors. If hydrogen process is certainly a solution to consider, it is not the sole one. In many cases, it is unclear whether or not other competitive technologies could be much less expensive for the system than the hydrogen path.

The needs for grid flexibility represent a limited market with little place for H2 in the short and medium term

One advantage of hydrogen that is often put forward is its ability to provide flexibility services. This flexibility might have several sources: variation of consumption of electrolysers, storage, flexible consumption... This flexibility could be beneficial to the power grid that is expected to have increasing flexibility needs to reach 2050 net-zero objectives.

In its report on hydrogen[24], the French TSO RTE, studied the need for flexibility that is expected in France and the potential role that could play hydrogen to meet this need for flexibility. They reached the following conclusions:

- The grid can absorb without problem the rising production of electrolytic hydrogen
- There should not be major flexibility need before 2030 and hence very few opportunities for flexibility-oriented hydrogen business models.
- After 2030, the market size for flexibility could increase but many competitors are expecting to fight for the market share (demand flexibility, batteries, electric vehicles…).

> There should be very little grid constraints that could prevent deployment of hydrogen in the short to medium term.
>
> One the other hand, little opportunities in power flexibility services for hydrogen should emerge in the short term as well. In the long term the competition will be very hard for flexibility and H2 might not be the most promising solution. This can nevertheless provide additional revenues for electrolysis projects.

H2 development could face timing issues

H2 can also face a **timing issue** in the short to medium term. As many of its potential usages are related to hard to abate emissions, they tend to belong to the sectors with the highest transition costs and longest investment cycles. As a result, we can reasonably expect that they would naturally correspond to the latest investments in the energy transition (both for system considerations of investment efficiencies and market consideration of price signal in the carbon market). This leads to 2 potential conclusions:

- The momentum for hydrogen in those sectors, if it ever exists, might be **more in the long term** (late 2030s or 2040s)

[24] (RTE, 2020)

- The time left could let some technologies improvements or breakthroughs emerge and change the overall competition landscape, either in favour of or to the detriment of hydrogen.

The transition to hydrogen is likely to have very high transition costs and might be postponed in the favour of least transition cost investments. Indeed, it makes sense to deal first with the least "hard to abate emissions sectors".

3.1.3.2 H2 value chain efficiency is low compared to its main competitors

The hydrogen economy requires many transformations across the hydrogen value chain, inducing losses at each step:

- Hydrogen production
- Compression at high pressure / transport / cooling
- Hydrogen usage

In particular, the loop "power to hydrogen to power" has a low energy efficiency. In order to be competitive, this poor efficiency needs to be compensated with a very cheap supply of electricity, which is far from being assured, alongside high utilization rate to amortize investment costs; or with very high electricity prices when the hydrogen to power solutions are functioning.

The efficiencies comparison between the power to hydrogen to power loop (used for power storage, fuel cell mobility, …) and the energy storage in batteries is clearly in favour of batteries (Figure 10).

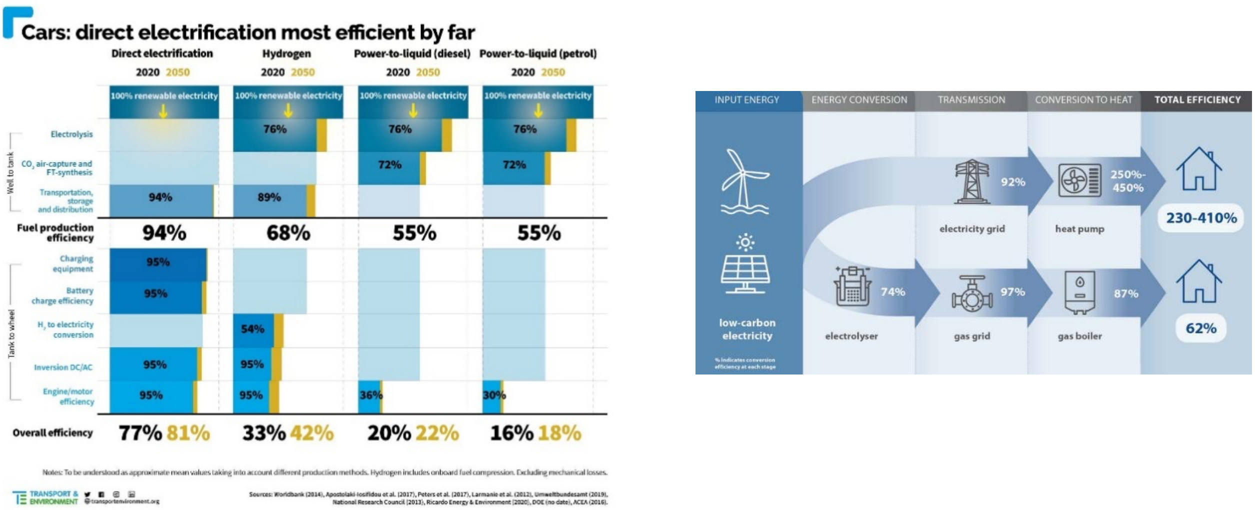


Figure 10: Energy efficiency of some H2 usages compared to direct electrification for transport[25] and space heating[26]

[25] https://www.transportenvironment.org/wp-content/uploads/2020/12/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf
[26] (Committee on Climate Change, 2018)

For the same power usage and all other things being equal, the hydrogen loop can require between 2 and 6 time more electricity than the direct electrification. This can have a big impact in sectors where the cost of energy supply is decisive. However, the differences in terms of usage and the total cost of the usage (with integration of the capex and the indirect costs) need to be taken into account.

The low theoretical efficiency of hydrogen process makes its usage costly and not very efficient for some usages. As those efficiency are hard natural constraints, little progress is to be expected.

3.1.3.3 Transition cost are high in all the value chain

Hydrogen technologies are expensive

One of the biggest problems with the green hydrogen economy is its costs. This can be divided into two subproblems:

I. **Green hydrogen is more expensive than grey hydrogen**. In some scenarios, green hydrogen becomes competitive with blue hydrogen in the long run [Figure 11], but for some experts, those assumptions are very optimistic in the favour of green H2 and we should not rely on that to expect the phase out of grey H2.
II. In most of the considered usages of the hydrogen, **the hydrogen-based processes are much more expensive than the carbon intensive alternatives** (steel, chemistry, …) and in some cases, it is also much more expensive than the green alternatives (light vehicles mobility…) [Figure 12]. Heavy duty transport is an exception.

Contrary to solar panels and wind turbines whose massive production over the last decades has rapidly enabled a production cost reduction, the production of almost all the components of the hydrogen value chain is very small. As a result, the costs are today very high and the expected decrease in cost is difficult to assess. It is commonly accepted that the pace of the cost reduction will depend on the pace of the production of hydrogen technologies that will benefit from a decreasing learning curve. Nevertheless,

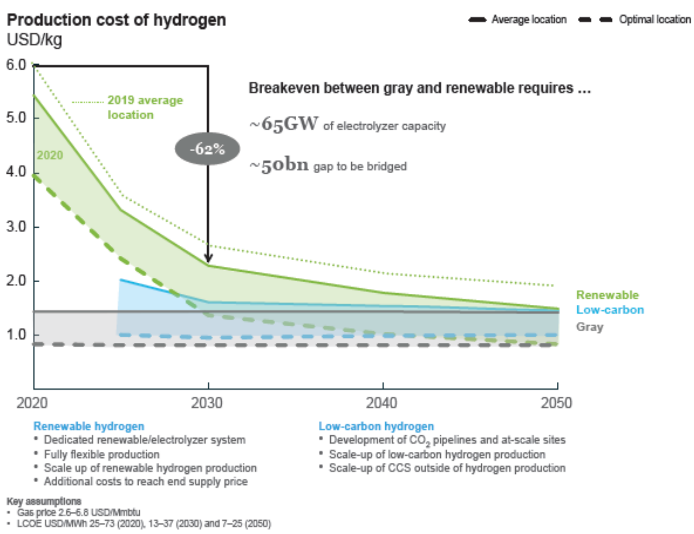


Figure 11: Production cost evolution of grey, blue and green hydrogen (Hydrogen Council - McKinsey & Company, 2021)

the long-term costs are very difficult to estimate[27].

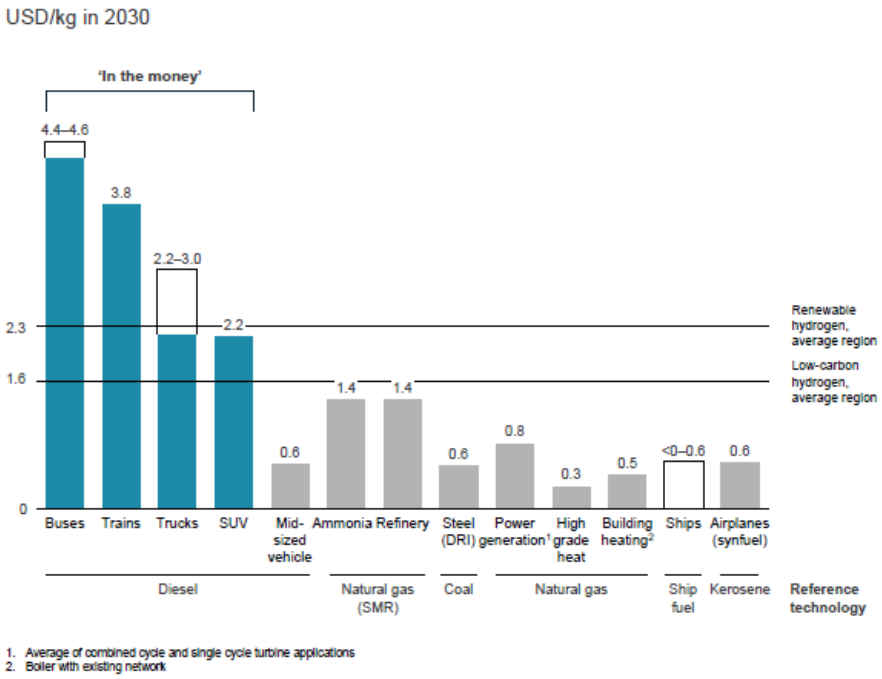


Figure 12: Required hydrogen production cost for breakeven with conventional solutions, without carbon costs. (Hydrogen Council - McKinsey & Company, 2021)

In paragraph 3.1.3.1 we analysed that hydrogen suffers from the conversion efficiencies it has to undergo across the value chain. These elements lead to the conclusion that hydrogen is expected to be an expensive energy carrier. If we put aside carbon emissions and focus on the economic impact of the technology:

- Blue hydrogen will be by construction much more expensive than direct usage of natural gas (additional process with loss, additional equipment, CO2 infrastructure, CO2 storage costs, …).
- Electrolytic hydrogen cost will depend on 3 key factors: the CAPEX of the electrolysers, the cost of power supply price and the full load hours. Those 3 factors can have jointly low cost in long term optimistic scenarios with a lot of renewable overcapacities. In other conditions, green hydrogen will remain a very expensive energy carrier.

[27] See for example (IRENA, 2020)

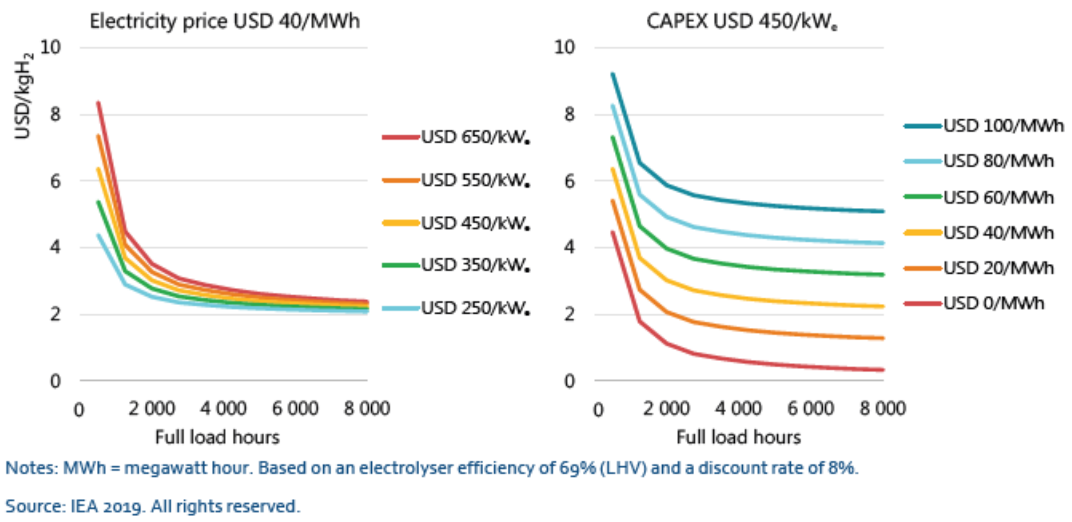


Figure 13: Future levelized cost of hydrogen production by operating hour for different electrolyser investment costs (left) and electricity costs (right) - (IEA, 2019)

The transport and distribution of hydrogen require significant investments

Transport and distribution of hydrogen is identified by many as an important bottleneck. No wide spread transmission and distribution hydrogen network exists today. Even at the local scale, only a few industrial focused hydrogen networks exist and they are concentrated around industry intensive regions. Contrary to natural gas and electricity for which widespread grids are installed, the transport and distribution of hydrogen would require new investments.

The expected hydrogen production is characterized by very important costs discrepancies between the different regions. Unfortunately, the regions with the most expected demand for H2 do not correspond to the regions where the production is expected to be the cheapest. This creates the opportunity for a large-scale hydrogen transport system to emerge. This opportunity will be covered in details in the paragraph 3.1.4.1.

The **existing hydrogen pipelines** are valuable assets and are clear opportunities to start-up a wider spread network. In Germany, Air Liquide and Linde operate hydrogen pipelines respectively in North Westphalia and Eastern Germany. Those infrastructures are connecting different industrial consumers (refineries, chemicals industries).

Repurposing of the gas pipes to transform them into pure hydrogen pipes could be a powerful way to create a new H2 infrastructure at a reduced cost. In the study “Hydrogen backbone”[28] conducted by Guidehouse for a group of gas TSO, the authors showed that the repurposing of parts of the current

[28] (Guidehouse, 2020)

gas infrastructure could lead to a significant reduction of the total investment required to build a hydrogen grid. Table 1 shows estimations from different studies.

Table 1: Table listing the LCOT for H2 transmissions in different studies. LCOT is defined as the discounted cost per MWh_{H2} transported. (European Commission - Guidehouse, 2020)

LCOT for H_2 transmission - refurbished natural gas infrastructure				
Units	**Value**		**Comments**	**Source**
EUR2019/MWh $_{H2}$ /600 km	3.7		Retrofitting existing gas infrastructure for 100% hydrogen.	(Guidehouse, 2019)
LCOT for H_2 transmission for new dedicated infrastructure				
Units	**Minimum**	**Maximum**	**Comments**	**Source**
EUR2019/MWh $_{H2}$ /600 km	4.6	4.6	48-inch pipeline. Includes pipeline and compressor CAPEX and OPEX and compression fuel-related costs.	(Guidehouse, 2019)
	9.6	9.6	34-inch pipeline with utilization of 75%. The source assumes the cost of transporting H_2 over 50 km. Normalised to 600 km.	(BNEF, 2019)
	11.4	11.4	Transportation over 1500 km is assumed by source, considering all capital and operating costs. Normalised to 600 km.	(IEA, 2019)
	16.1	49.8	Pipeline with a capacity of >100 t/day. The source assumes a 100 km pipeline. Normalised to 600 km.	(BNEF, 2019)
	45.0	45.0	Estimated including compression costs for pipes of diameters between 7-10 inch over 100 km as assumed by source. Normalised to 600 km.	(DNV GL, 2019)

A large H2 infrastructure would help synergies materialise:

- Optimisation of H2 LOCH by exploiting the resources of the best endowed regions and therefore reduce the overall production costs.
- Enable the creation of an H2 market, with financial products to edge against the risks taken by the different parties.
- Simplify the business model of H2 producers who could inject their production into the network.
- Simplify the business model of the off takers who would not need to contract with a dedicated producer for its H2 supply.

Major improvement of transport cost can be game changer. For example, it could trigger international trading of hydrogen via the establishment of hydrogen markets. This point will be studied in more details in Section 4.2.

Transition costs are very high across all the value chain: production, transport, usage. For many usages the cost of transition might be prohibitive.

3.1.3.4 A technological bet?

Even though hydrogen is expected to remain very expensive, there is a clear momentum to support H2 technologies. This is partially due to public support with motivations that have been listed in Section 3.1.2.4. The industrial sector, but also investors, are currently investigating the interest they could reap in hydrogen deployment. This momentum is very important to start up the sector and enable rapid cost reductions. The multiplication of recent projects is a sign of the current momentum[29].

Nevertheless, nothing proves that the cost reduction in hydrogen technologies and technology evolutions to enable more use cases for H2 will meet the expectations. The impressive learning curve that we experienced for solar and wind turbines should not make us believe that a complete collapse of costs is inevitable for hydrogen technologies.

A lower-than-expected cost reduction could jeopardize the relevance of hydrogen for the system in many applications.

Cost reduction and current momentum for hydrogen can help to develop the value chain. However, the risk of lesser than expected cost reduction could jeopardize the whole hydrogen

3.1.3.5 H2 can be a dangerous gas to handle and requires specific attention

The chemistry characteristics of hydrogen raise some security issues. Indeed, dihydrogen gas (H2) is characterized by:

- A very small size of its particles, which makes it **very difficult to prevent leakages**. Nevertheless, the gas is so light that it would not accumulate itself in non-confined places in case of leakages, reducing the risks of explosions.
- H2 gas is **odourless** and **colourless** gas, which raises some security issues as it is difficult to detect. For some experts, the purity levels required for H2 usages like fuel cells are so high that

[29] https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

it would be very difficult to add odourising elements to hydrogen like it is done today in natural gas networks.

- High reactivity characteristics.

If H2 is commonly used in an industrial context, its handling by the general population raises many concerns. **Strict regulation will be required to prevent any risk but this might mitigate the pace of hydrogen adoption and increase the costs**. Developing projects with the highest security standards is key **to gaining public acceptance.** A number of interviewed experts have suggested that a major accident with fatalities could kill the market for years. For example, a recent deadly accident in a hydrogen station in Korea has triggered a rejection of pro-hydrogen policies in the country[30].

The safety concerns could also cause a **NIMBY effect** (Not in my backyard). This difficulty of public acceptance could delay significantly the development of projects near residential areas (typically hydrogen refuelling stations).

For many experts, safety issues question the usage of hydrogen for residential heating applications.

Hydrogen safety issue are real and should not be either underestimated or instrumentalized against hydrogen. The hydrogen projects should be developed with a strict security framework to unsure the development of the sector in the best conditions of safety and public acceptance.

3.1.3.6 Other weaknesses of hydrogen for the system

The carbon impact of electrolytic H2 is not so clear

Hydrogen is not primary energy source: there is no discovered hydrogen source on earth that could be exploited (at least not for the moment). As a result, all the hydrogen consumed must be previously synthetised. If the carbon emissions of using hydrogen are null, this is not necessary the case for the production of this gas. As a result, the following saying is often associated to hydrogen:

“Hydrogen is as clean as the technology used to produce it”

If this sentence is mostly true some nuances can be brought:

30 https://www.reuters.com/article/us-autos-hydrogen-southkorea-insight-idUKKBN1W936A

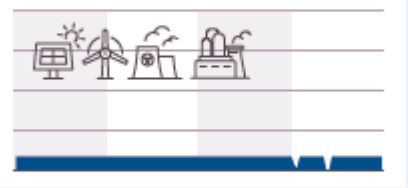
- To this production aspects we should not forget **the whole value chain** between the production and the consumption (transport, compression, storage) which also have an impact in terms of energy consumption, material usages, CO2 intensity, etc.
- **In the system point of view, the carbon impact of green hydrogen (electrolytic hydrogen using only power from renewable energy sources) is not necessarily zero**. Indeed, if renewable electricity is diverted towards electrolysis, leading to smaller exports towards heavily polluting power systems, the overall emissions can rise. The following box explores some of the production business models of electrolytic H2 that highlight this problem.

Business model for electrolytic H2 (RTE, 2020)

In the study ***La transition vers un hydrogène bas carbone***[31], RTE explores 3 distinct business models for electrolytic H2.

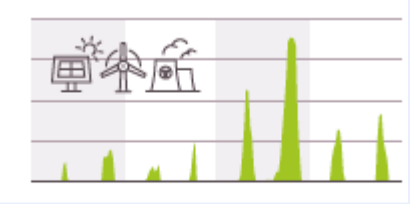
1. Base load consumption on the grid

The electrolysers use the power from the grid unless in a limited number hour hours when the prices are high.



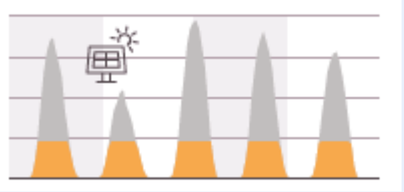
2. Grid consumption in low prices only

The electrolysers use the power from the grid only when the prices are very low. This corresponds to hours when renewables or nuclear productions are marginal.



3. Off grid consumption of dedicated RES production

The electrolyser project has its own associated renewable production.



In a system point of view, the solutions 2 and 3 of the above table may seem carbon neutral whereas the first solution induce consumption of carbon intensive power. The carbon intensity in the first situation depends nevertheless on the power generation mix.

Besides the carbon content of electricity used to produce this hydrogen, the important question to assess the real carbon impact for the whole system is:

[31] (RTE, 2020)

"Is hydrogen the best way to use the carbon free electricity production? "

Indeed, the power used to fuel the electrolysis could also be used to supply carbon free power to another consumer (and eventually help to electrify more usages). As a result, this "lack of electricity" for the power system needs to be compensated by other sources which induce additional capital expenditure and sometimes additional carbon emissions.

- In the model 2 the price signal ensures that this consumption of electricity for the electrolysis will be compensated by a carbon free production of electricity. Indeed, if a carbon intensive plant were needed to compensate for this consumption, then the electricity price would rise and the electrolyser would stop its production.
- In the model 3, if the electricity is consumed when carbon intensive power productions are working, then this electricity could have been used to reduce those carbon intensive emissions on the grid if the dedicated RES sold its production on the grid instead of fuelling the electrolyser. In this situation, the production of electrolytic H2 has a systemic CO2 impact compared to the situation without electrolyser, even though its electricity is produced with carbon free production. This impact can be compared to the CO2 impact of carbon intensive production of H2. There is in fact very little room to be carbon efficient when comparing to the classical SMR based production of hydrogen (see box below).

What is the CO2 abatement of electrolysis?

With the following assumptions:

- H2 energy per unit of mass (LHV): 120.1 MJ/kg = 33,36 MWh/tH2
- Average carbon intensity of hydrogen production using natural gas of 10 tCO2/tH2 = 0,2998 tCO2/MWh (LHV) of H2

***Maximum carbon intensity of power to be CO2-competitive with SMR*:**

Electrolysis efficiency (LHV)	*40%*	*50%*	*60%*	***70%*[1]**	***80%***	*90%*
Maximal carbon intensity of power to match the intensity of SMR [gCO2/kWh]	120	150	180	210	240	270

As a result, in the model 3 (dedicated RES model), if an electrolyser with a 60% efficiency produces hydrogen in a period where the marginal producer of electricity is an OCGT (with a carbon intensity of 352 gCO2/kWh), the CO2 impact on the system point of view is in fact **2 times greater** than with a classical SMR without any carbon capture.

In some configurations, grey H2 can have a lesser CO2 impact than electrolytic H2

A solution that is often proposed to solve the issue is to **make sure that the RES investments follow the pace of electrolysis installations**. This solution has been formulated inside the "**additionality principle**" that forces to couple investment in electrolysis with investment in additional renewable capacity. First introduced in the context of RFNBO production, this principle can help the power mix adapt to electrolysis. We will explore in more details this principle in Section Should we regulate the

> The carbon efficiency of electrolytic H2 is not easy to estimate. Even green H2 may not be carbon neutral for the system on the whole. In the system point of view, in order to reduce carbon emissions, the priority is to decarbonise the power system before developing green H2.

market now?3.1.4.2.

Blue H2 remains a controversial subject

The possibility to use blue H2 in the hydrogen strategy is very controversial. In the long term, **many see no place for it as it does not comply with climatic goals**. In its *Hydrogen strategy for a climate neutral Europe*[32], The European Commission states:

> *"The priority for the EU is to develop renewable hydrogen, produced using mainly wind and solar energy. Renewable hydrogen is the most compatible option with the EU's climate neutrality and zero pollution goal in the long term and the most coherent with an integrated energy system.".*

The idea that blue hydrogen could play a role in the short to medium term is more often accepted and will be covered in Section 4.1.2.

The interest of Blue Hydrogen remains a subject with very little consensus. It is both seen as non-compatible with global ambition and key elements to reach those very same ambitions.

3.1.4 Many questions remain unanswered to have a better vision on H2's future role

Besides is current usage as feedstock for some specific applications, hydrogen usages would mostly be new ones. Like all new technologies, hydrogen carries uncertainties and risks, especially given that the business models remain unclear today. These as-of-yet unanswered questions are as many threats and opportunities for hydrogen.

3.1.4.1 What infrastructure for H2 in the short-medium and long term?

A subject that is very often at the centre of discussions when it comes to hydrogen is the necessity of H2 infrastructure. **For some stakeholders, we should build a "gas-like" hydrogen model with large transition pipelines across Europe and local distribution networks inside the different countries**. At the other extremity of the spectrum, **some experts defend the idea that the infrastructure would be a poor investment in energy transition as hydrogen is likely to be produced locally, mostly within industrial clusters**.

[32] (European Commission, 2020)

Will it be a local system or a global system?

The first element that could provide insights about this question is the concentration of the expected demand and its volume.

- **Case 1**. If hydrogen usages are only very specific to some industrial or maritime usages, a concentration of hydrogen networks near industrial clusters (harbours and the industrial valleys) should cover most of the needs.
- **Case 2**. If hydrogen usage is wide spread (mobility, heating, etc), then a global infrastructure could be a very efficient way to reduce the production costs of hydrogen by transporting it from efficient production centres to consumers.

For many experts, **hydrogen development is likely to unfold in a two-step process**. At first, the usages should remain limited to some industrial usages like in Case 1. In the study *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*[33] from the Energy Transitions Commission, several archetypes of these clusters are identified:

- *Refining, petrochemical and fertiliser clusters*
- *Ports*
- *Non-coastal transport nodes, often close to major cities*
- *Steel plants*

If the demand for hydrogen continues to increase and new usages to develop, then the clusters will start to connect to one another to benefit from scale effect. **Little by little, we would switch to Case 2 by connecting the clusters one after another to gain efficiency and connect additional consumers and producers.**

As the transport of hydrogen is costly, this gas will be transported through long distances only if it makes the system benefits from large volumes of much cheaper supply. **Energy highways** under the form of hydrogen could appear to take the most advantage from the regions with the most efficient RES production. For example, a hydrogen pipeline connecting the Ruhr area to Algeria could provide to German consumers a hydrogen supply at a cost around 1,9 USD/kgH2 as soon as in 2030 according to the Hydrogen Council's *Hydrogen insights*[34].

Historical perspective of H2 development

In order to obtain a clearer vision on how the hydrogen system could be initiated, **we can try to compare its expected development to the development of energy vectors in the past.** The table

[33] (Energy Transition Commission, 2021)
[34] (Hydrogen Council - McKinsey & Company, 2021)

below explores some characteristics of the development of power, natural gas and hydrogen in Europe.

	Power	Natural Gas	Hydrogen
Existing demand prior to the deployment of the new energy vector?	No	Yes (town gas)	No
Possible local Production?	Yes	No	Yes
Transport of the commodity is expensive	Yes	No	Rather not

At least in the medium term, hydrogen is very unlikely to have the same role as natural gas in the European energy supply mix. Indeed, the gas system is composed of some countries in western Europe with very high demand for natural gas but no production (expect for UK and Netherlands). Most of the gas is imported from a few regions (mainly from Russia, Norway and North Africa) through pipelines. On the other hand, electrolytic hydrogen can be produced locally (and the political agenda is pushing forward this "local production" narrative). As a result, transport infrastructure might not be at the core of hydrogen economy, but will eventually enable cheaper hydrogen supply if a price spreads developpe between regions.

As far as developing a completely new network is concerned, hydrogen has very little to do with the natural gas system. Indeed, when the European natural gas was developed, the goal was to import large amounts of this new commodity from big production centres (namely Soviet Union, the North Sea, etc.) directly to Central and Western Europe. Prior this natural gas development, town gas had already been used for decades in European cities, and was produced from coal, locally in dedicated gas plants .

The situation for hydrogen is very different today as no consumption (or very little) exists today besides large industrial off takers. In this regard, **the development of hydrogen network is expected to be similar to the past development of power network: a spread around existing clusters**.

The power networks first developed locally in many places next to some production areas (early plants supplying the local needs). The power networks then spread as the usages of power grew (many new appliances appeared) and the local networks started to connect to each other's and eventually merged to form big networks. Those characteristics of the development of the power networks in western Europe are very similar to the characteristics that are expected for the hydrogen system.

In many aspects, hydrogen network development has very little to do with historical development of natural gas networks in Europe. The historical comparison with the development of power networks seems much more interesting.

The opportunity of blending: decarbonising technology with little investment needs?

Blending refers to the admixture of hydrogen with natural gas, directly into the gas network, up to a certain H2 concentration. This solution benefited from a great interest in the past few years in despite of the critics of experts.

WHAT CAN BLENDING ACHIEVE?

The theoretical justification for blending is straightforward: by replacing a carbon intensive gas by a carbon free gas with similar characteristics, we are able to partly decarbonize the gas system. This solution has a great interest for different actors:

- For gas companies and gas networks companies, blending is a way to promote decarbonisation through the current gas system. **Even in the context of decrease of the use of conventional methane to reach carbon emissions targets, the gas networks would remain a very important asset** that requires investments.
- **For H2 project developers, it is the opportunity to inject their production into the network in a simple "*bio-methane like*" business model**. By doing so, they would not have to find consumers for their production (which is the key bottleneck of the hydrogen economy as we will see in paragraph 3.2.3).
- Blending can be seen as a kick-starter of the H2 sector, without any dedicated infrastructure.

IS BLENDING EVEN POSSIBLE?

Juste like in most of the energy fields, blending is theoretically possible. But the relevant questions are "to what extent?" and "at what cost?". Many studies have tried to evaluate the theoretical maximum level of blended H2 in the gas network and the corresponding costs. The current consensus is that beyond 20% in volume, blending would require heavy investments.

IS BLENDING DESIRABLE?

As we saw previously, blending is a solution with many advantages for gas networks and H2 project developers. Nevertheless, for the system in general this solution might not be as promising for many reasons:

- H2 and natural gas do not have the same calorific value. As a result, **blending hydrogen in natural gas reduces the calorific value of the natural gas**. This calorific value decrease has some consequences:
    - Some settings could be required to adapt appliances and industrial machines
    - For DNOs, the fair tariffication of customers will be more complicated because of the heterogeneity of calorific values across the network.
- Even if we limit the H2 concentration under a given security level, it would be very complicated to manage the exchanges between countries with different blending levels. Taking a single level for everyone would require to make sure that the common concentration do not cause any risk anywhere in the network**. It is also important to make sure this constraint is met everywhere in the network**, and especially near the injection points and the regions expected to be H2 producing regions. This would in fact mean that the maximum level inside a country is on average much lower than this theoretical maximum level.
- **Will it really be compliant with all the gas usages**? For example, in gas storages, will the H2 separate from CH4 and can we ensure that the concentration of hydrogen is low enough when the gas is extracted from the storage? This question is also a concern for gas appliance (and especially those in households). Are we sure that H2 will not leak from gas taps and tube in the old houses, risking to reach dangerous concertation inside a confined area?
- The H2-gas mix, in addition to material resistance, leakage and security issues also induces appliances issues. **Many industrials are strongly against H2 blending as they need a certain quality of gas to run their processes that were optimized to natural gas current composition**. Even at low H2 concentrations some of them would need to de-blend methane from hydrogen (with additional cost and energy consumption) or change their industrial assets.
- Blending implies to mix a very expensive and hard to produce gas like hydrogen into the much cheaper and widely available natural gas. This process induces a significant dilution of the value of hydrogen. The market incentives for blending should hence be very small.
- The carbon reduction of gas is only relevant if the hydrogen is produced with a business model inducing very low levels of carbon emissions, this excludes therefore many production solutions and even some electrolytic H2 business models (see paragraph 3.1.3.6). Hence in a systemic point of view, blending only reduces the carbon emission if the blended hydrogen was produced in periods of renewable electricity production without requiring more carbon-intensive generation technologies to start. We can also wonder whether the timeline is relevant given that blending is often seen as “the early stage” of hydrogen development.

Blending has many drawbacks and a low decarbonization potential. Moreover, it is a short-term solution as natural gas related emissions need to be tackled down very quickly to be compliant with EU's strategy. This contradicts the fact that blending has a systemic positive impact on carbon emissions only if the power system is already largely decarbonate, which is not likely to happen in the short term.

Planning of infrastructure needs

As many expect hydrogen to play a major role in the energy system, the creation of a dedicated H2 regulation framework seems relevant. Owing to the major the differences with natural gas, **many experts ask for an independent H2 regulation framework**.

The hydrogen development requires a long-term coherent vision. As a result, **many ask for an infrastructure planning similar to those performed either by ENTSO-E and ENTSOG (TYNDP).** But as hydrogen is at the interface of the power and the gas system, the future infrastructure planning would need to have a coherence between the energy vectors**. A common TYNDP for power, gas and H2 is a solution often stated as being required for an efficient planning of infrastructure to materialise**. An infrastructure planning exercise at the European scale is also seen by many as a powerful tool to prevent a patchwork of several incompatible regional plans.

Nevertheless, some experts we have interviewed have identified the risk to have a **biased long-term vision on hydrogen** if the infrastructure planning is let either to the gas or to the power ENTSO.

Risk of over investment in infrastructure

Given that we are not sure of the real place that hydrogen will play in the long term, and given the controversies between experts to estimate if a global hydrogen infrastructure is needed instead of small local hydrogen systems, there is a debate on the targeted level of infrastructure. For many, **we face a high risk of overinvestment in some infrastructures** that will not be useful in the short to medium term (and perhaps never will). This would lead to **new stranded assets** which could become a new burden to the energy transition.

Agora in their study *No-regret hydrogen - Charting early steps for H2 infrastructure in Europe*[35], Agora Energiewende and Afry gave a first answer to this problem by estimating a level of "**no regrets infrastructure**". Their methodology focused on H2 usages that have the most consensus among experts: industrial usages with a focus on refining, ammonia, methanol, chemicals plastics recycling and steel. This study is particularly interesting as it provides a first methodology to estimate the required future hydrogen infrastructure taking into account the current hydrogen infrastructure, the

[35] (Agora Energiewende - Afry, 2021)

expected localisation of hydrogen demand and the expected production capacities of hydrogen. They found out that very little new infrastructure should be required [Figure 14: Clear "no-regrets" routes found out in the study Figure 14].

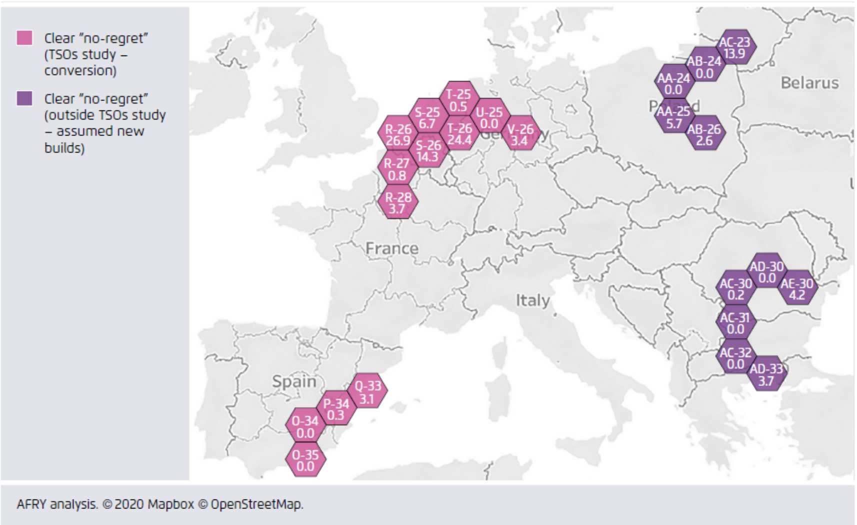


Figure 14: Clear "no-regrets" routes found out in the study (Agora Energiewende - Afry, 2021)

The systemic risk of "lock-in effect"

The promise that hydrogen could replace natural gas in many of its current usages has an insidious downside. Indeed, we face the risk **that if the hydrogen does not fulfil its promises, then many sectors would be locked in carbon intensive usage habits with very little room for improvement and very little time to switch to alternative carbon free solutions such as direct electrification**. This so called "**lock in effect**" is identified as a significant threat for the heating sector. Indeed, the perspective of large amounts of the current gas heating being switched to hydrogen in 10 to 20 years is an incentive to keep the "as is" situation and heating habits. The heating sector would then face a very complicated issue if after 10 to 20 years, the conditions are still not met to provide cheap hydrogen-based heating in households.

> *"Betting on the future large-scale availability of hydrogen and e-fuels risks a lock-in of fossil-fuel dependency if their upscaling falls short of expectations. Hydrogen and e-fuels are a potential distraction from the urgent need for an end-use transformation towards wide-scale direct electrification, […]"*[36]

In some sectors, the hydrogen prospects can induce a lock in effect on some carbon intensive energies. This carries a systemic risk to miss our carbon targets if hydrogen fails to fulfil its promises.

[36] (Ueckerdt, 2021)

3.1.4.2 Should we regulate the market now?

Regulations under discussion

Today the energy markets (for gas and electricity) are strongly regulated in Europe. The **unbundling laws** impose the separation the activities with a natural monopoly (networks activities like TSOs and DSOs) from the activities that are put in competition (production and selling).

The question of the opportunity to impose similar regulations for the emerging hydrogen economy can be raised.

Today the existing hydrogen markets are operated by big integrated companies like Air Liquide or Linde that manage the production, the network operations and the selling of hydrogen to their portfolio of industrial clients.

An open access to those existing hydrogen networks would enable producers to inject their production, facilitating the scaling up of hydrogen production and enhancing competition to decrease the costs compared to this monopoly situation. ACER in its report The Bridge Beyond 2025[37] states:

> *"New assets and activities should be facilitated through regulation, including a sandbox model at EU level for pilot, small scale projects and appropriate differentiation between competitive and monopoly activities. Any subsidies are a matter for governments rather than regulators, and should not take the form of discounts on or exemption from network tariffs in any case. TSOs and Distribution System Operators (DSOs) should only be allowed to undertake potentially competitive activities under strict rules and as a last resort. While it is too early to be definitive, large-scale hydrogen networks could be expected to provide regulated third party accessing."*

On the other hand, many experts point out that an **early and constraining regulation could jeopardize the development of the market which is at an early stage and struggle to find any viable business model**. Moreover, the unbundling regulation approach is difficult to adapt to a gradual development of the network that spreads itself by the connection of independent networks islands like described in section 3.1.4.1.

[37] (ACER, 2019)

Another regulation that is often quoted in the field of hydrogen is the "**additionality principle**" under which every investment in electrolysis should be back up by investment in additional capacities. Besides the risk of misallocation of capital (as the investments are less market based), this principle is foreseen to potentially reduce the profitability of hydrogen project developer, and to increase the barriers to entry, inducing a systemic supply issue. This regulation has been clearly identified as a major risk for the hydrogen project developers (see paragraph 3.2.6.2).

Early regulation could be harmful to the development of hydrogen sector. A strict additionality principle is also identified as a major risk for the development of H2 projects.

Technology neutrality?

Many different production methods and different business models exist for the production of hydrogen. As those differences induce different CO2 impacts, many experts ask for a clear distinction of the different production methods. Others prefer **to take into account the real carbon content of the produced hydrogen instead of the sole production method**. This approach seems more accurate as it takes into account the countries' specificities that have very different power systems characteristics.

In the report the Bridge Beyond, ACER clearly favours the neutrality approach:

> *"A technology-neutral, level playing field should be established between different conversion and storage facilities across the energy sector, so that they face equivalent categories of costs in network tariffs and levies, and equivalent recognition of environmental and security of supply benefits."*[38]

The absence of technology neutrality can also induce many backslashes:

- Misallocation of capital.
- Absence of flexibility toward new emerging production means that could enter the market.
- Reduction of the supply potential by preventing some sectors like blue H2 to develop at its full potential.

The taxation of CO2 emissions is in itself a powerful tool to set an optimal target of investment and reach carbon emission objectives at minimal cost. On the contrary, a technology-biased policy could induce results in contradiction with the carbon reduction objectives.

[38] (ACER, 2019)

The lock-in effect on non-carbon neutral technologies is often raised as an argument for policies favouring green hydrogen. For example, many quote that no switch from blue H2 to green H2 will be possible if the system is developing itself around a classical steam methane reforming ecosystem. Some strongly mitigate this argument and think that this effect would be not that strong if the market conditions turn in the favour of green H2 compared to low carbon H2. In his May 2021 article for the Oxford Institute for energy studies issue 127 of the "Quarterly journal for debating energy issues and policies", Alex Barnes concludes: "*Government policy is easily capable of ensuring that renewable hydrogen is preferred once there is sufficient supply—by increasing the cost of carbon, subsidizing renewable hydrogen more than low-carbon hydrogen, mandating the use of renewable hydrogen, or a combination of all three. The risk associated with stranded assets for low-carbon hydrogen is not that it will preclude the use of renewable hydrogen but that it will prevent companies from investing in low-carbon hydrogen at all, which means delaying the switch from unabated fossil fuels to lower-carbon energy, prior to a final switch to renewable hydrogen once it is sufficiently available.*"[39].

Finally, some ask for a non-neutrality in the demand side by **routing the H2 production to some specific applications**. For example, many ask to prevent hydrogen from being used in domestic cars and to concentrate its usage in hard to abate emissions sectors. This argument has its exact opposite considering that markets by nature and price discovery will ensure that **hydrogen will supply in priority the hydrogen demands associated to the highest value** and the highest willingness to pay. If the carbon reduction objectives, as a value for the system, fail to create a willingness to pay (or a value for the actors), the two arguments will remain in opposition.

On the contrary, **a non-discriminant market enables the optimal usage of the resource**. The widespread idea that hydrogen will be by nature a scarce resource is also to be questioned. Hydrogen only requires RES production and water. Those two resources are almost limitless in Europe (or at least it is only limited by the resources of power generation). The real scarcity will be for the production of "cheap hydrogen" but this is a common characteristic of many commodities around the word.

Interest of having a regulated H2 market:

An H2 market open to all at the image of what we have today with power and gas would greatly stimulate the competition leading to price reductions and larger adoption. Nevertheless, it remains very tricky to organise such a market at an early stage given that very few transport capacities are available. Indeed, such markets require well defined "physical" delivery points. Without an integrated, international transport system like the hydrogen backbone[40] described in Guidehouse's study, this kind of market seems out of reach.

[39] (Barnes, May 2021)
[40] (Guidehouse, 2020)

3.1.4.3 What kind of support mechanisms will be the most suited?

At different levels, support mechanisms are put in place to enable the energy transition. Some mechanisms such as the European Union Emissions Trading System (EU ETS), which aims at giving a price to CO2 emissions, are already in place. Other support mechanisms are under evaluation.

EU ETS

The EU ETS is a powerful tool to get a market price of carbon emissions and optimize the investments toward the reduction of CO2 emissions while ensuring technological neutrality. As far as hydrogen is concerned**, the increase of the EU ETS could have a negative impact on the development of H2**.

Indeed, the EU ETS has a big impact on power prices that are most of the time set by the marginal gas power plants. **Given the efficiency of gas power plants, the carbon taxation has in fact a bigger impact on the electricity prices and than on the gas prices as long as the renewables power production are not the marginal producers for significant amounts of time**. Even the supply cost of green H2 under PPA would be impacted as the power producers will adapt their selling prices to the prices they could obtain on the spot market. Given the difference in efficiency between the SMR and the green hydrogen production chains, **it is likely that, at leat for some time, the impact of high CO2 prices will be greater for green H2 than for classical carbon intensive methane reforming facilities**.

Carbon Contract for Difference (CCFD)

Another solution that is preferred by some experts is the development of a **Carbon Contract for Difference (CCFD)**. Those contracts are described as such in the European commission publication A Hydrogen Strategy for a climate neutral Europe[41]:

European Commission on CCFD: (European Commission, 2020)

"With the need to scale-up renewable and low-carbon hydrogen before they are cost-competitive, support schemes are likely to be required for some time, subject to compliance with competition rules. A possible policy instrument would be to create tendering systems for carbon contracts for difference ('CCfD'). Such a long-term contract with a public counterpart would **remunerate the investor by paying the difference between the CO2 strike price and the actual CO2 price in the ETS in an explicit way, bridging the cost gap compared to conventional hydrogen production**. Areas where a pilot scheme for carbon contracts for difference can be applied is to accelerate the replacement of existing hydrogen production in refineries and fertiliser production, low carbon and circular steel and basic chemicals, and to support the deployment in the maritime sector of hydrogen and derived fuels such as ammonia and the deployment of synthetic low-carbon fuels in the aviation sector."[…]

[41] (European Commission, 2020)

With this mechanism, the industries are given a premium to help them reach the breakeven point after having switched to a carbon free solution. Hence, **industries that would switch to carbon neutral solution if the CO2 prices were higher, are incentivised to invest earlier and with fewer risks**. This mechanism can be a very efficient regulation as it enables to:

- Gain a few years on investments.
- Remove the CO2 price volatility factor.
- In the system point of view, **the progressive growth of the CCFD strike prices ensures a coherent allocation of capital as the investment with lowest cost of avoided CO2 emissions will be done first**. The optimal allocation is performed across sectors, across plants and across substitution technologies.
- In a long-term objective to decarbonise all the sectors, the CCDF strike prices can even depend on the sectors, ensuring that all sectors start decarbonisation process early. With sectoral differences in CCFD strike prices, we nevertheless lose the optimal allocation of capital across the sectors.

CCFD is not an insurance that H2 processes will develop, as it is precisely designed to invest in the most efficient solution for carbon reduction. In some sectors, it could even reduce the current growth prospects for H2.

This solution has nevertheless some drawbacks:

- Destruction of capital as some equipment's are phased out earlier than expected.
- Increase of production cost in a system point of view.

Direct support schemes

Direct support schemes for renewable hydrogen are also a solution. The allocation of those subsidies by a market mechanism could unsure the incentive to reduce the costs. The European Commission stated[42]:

> *"Market-compatible support should be coordinated within a transparent, efficient and competitive hydrogen and electricity market that provides price signals that reward electrolysers for the services they provide to the energy system (e.g. flexibility services, augmenting renewable production levels, reducing burden from renewable incentives)".*

[42] (European Commission, 2020)

3.1.4.4 Systemic impact of H2 usage in the industry

H2 based industrial processes will be more expensive than the current carbon intensive processes. In order to meet the carbon emission targets, some mechanisms are expected to be put in place to somehow force the industrials to switch to H2 (either because of carbon taxation, emission quotas, specific regulations…). This rising production cost is expected to have many economic consequences:

- Increase of prices for the final users and therefore reduction of the global welfare (climatic impact being excluded).
- Structural growth of industrial goods prices as we would use more resources (both physical resources, human resources and natural resources) to get the same amount of industrial goods. This effect could be balanced with a sharp growth of productivity that could for example come from digitalisation.
- Decrease of production quantities (as production cost will rise) and therefore decrease of benefits and high risk of labour reductions.
- The loss of competitiveness of the local industries compared to their international competitors will induce the **fall of their exportations**. This will again reduce their revenues, benefits and put pressure on the labour forces. Moreover, the local demand for the goods could be supplied by more competitive industries abroad, resulting in the complete fall of local production.
- The global reduction of industrial exportations would have an important impact on the countries trade balances, inducing several monetary and financial issues. It would also reduce our ability to import goods and services from abroad, all other things being kept equal.
- It can jeopardize the energy transition as it will be much more expensive to use concrete, steel and other materials essentials to the energy transition (for transport infrastructures, new buildings, wind turbines, new cars etc…). Moreover, the reduction of exportation and the destabilisation of the trade balance could make it more and more complicated to import essentials good for the energy transitions such as solar panels, batteries, some important raw materials etc…

Border carbon adjustment mechanism (CBAM)

In order to handle these drawbacks, some mechanisms are under consideration, but none seem to solve all the issues. A solution often given to protect local industries switching to carbon free industrial processes is the implementation of a **carbon taxation mechanism at the border of the EU**. In addition to the legal issue of such a mechanism given the current international treaties, this solution has in fact a limited action and could even have a systemic negative impact.

This taxation mechanism in its simplest principle would consist in taxing the goods imported proportionally to the amount of CO2 that were required for their production. This is a way to **compensate for the lack of competitiveness of EU industries which undergo massive investments for decarbonization and higher OPEX due to the fossil fuels phase out**.

Among all the issues listed above, this solution would in fact only make sure that the local demand would be supplied by local industries (or at least industries with the same carbon constraints). All the other issues will remain with this simple formulation of the mechanism (higher costs, lower production, structural rise of prices, decrease of exportations, …).

The measure could also in the worst case, induce **retaliation from the countries** considering that this is an **unfair trading limitation design to remove their own industries from the European market**. Those countries could therefore adopt some counter trading measure and limit for example the trading of important goods to Europe like solar panels, batteries, chips, etc.

3.1.4.5 We should take care of misallocations of capital

It is widely accepted that the development of the hydrogen sector to the levels projected will require massive amounts of public support and subsidies. The risk of misallocation of capital will hence be very high as the market will not play its role of investments selection. The risk of misallocation of capital is particularly high if the policy makers lack of awareness about hydrogen and energy markets.

Some experts consider that **the multiplication of local pilot projects dedicated to research could have the vicious effect to spread misconceptions on the real hydrogen prospects** and influence the policy makers toward poor choices of capital allocation for the energy transition.

3.1.5 Some game changer elements are identified and can completely change the situation

Experts points out that a few game changer events could completely disrupt the current appreciation we have of the hydrogen perspective. Those events could have either a very positive or very negative impact on hydrogen. The experts we interviewed have identified **4 game changers** for the system:

- Cheap long-distance trading of H2
- Explosion of the H2 bubble
- Development of alternative models where hydrogen has very tiny prospects
- Massive adoption of Small Nuclear Reactors or nuclear revival.
- Unknown Unknows

Cheap long-distance trading.

If the problem of hydrogen transport at minimal price is solved, then the market landscape prospects could change dramatically. The long-distance maritime transport of hydrogen is pointed out by experts as one key disruptive technology. If this technology truly emerges at cheap prices, then hydrogen could be produced in very sunny areas where the cost of renewable energies is very low and where industrial facilities of gas trading already exist: Qatar, North Africa, Texas … In this situation we could have much cheaper hydrogen supply for consumers, but in the other hand, almost no local producer of hydrogen would be cost-competitive compared to long-distance suppliers.

Risk of explosion of the hydrogen bubble

If the hydrogen bubble explodes because outcomes do not match expectations, it could be an important problem for all the stakeholders involved in this sector. The momentum could completely vanish and political support could switch to other technologies. Without support, the financing of H2 project could become more and more complicated as the prospects become less and less appealing. Without political and financial support, hydrogen chances to kick start are very low. That is why a brutal explosion of the bubble could devastate the sector for years or decades.

Development of models where hydrogen has very tiny prospects.

Hydrogen will be in competition with many alternative options and we cannot say which solution will emerge as the winner. One solution that has the potential to completely question the role of hydrogen in many applications is the development of carbon capture and storage. If CCS can be used directly in industries and in gas power generations, then we do not have this need for carbon free fuels like hydrogen. We could very well concentrate the decarbonisation efforts at the end of the value chain trough either storage, transformation or usage of the carbon dioxide. This CO2-based energy system would shrink the place that hydrogen has in a carbon free model.

Massive adoption of Small Modular Nuclear Reactors.

The Small Modular Nuclear Reactors remain currently at a very early stage and time will be required before the first real applications. Yet, many investors believe in this technology that could provide directly heat and power with high safety standards. Yet, many hurdles need to be crossed like cost reduction and public acceptance. The revival of the nuclear sector that can provide a stable and dispatchable source of carbon free power must also be taken into account. Nevertheless, some experts point out that **Small Nuclear Reactors could be this killing technology with the potential to turn the tables completely in the energy system**.

Unknown unknows

Like in all long-term projections, the biggest threat for hydrogen could in fact come from a cause that has not yet being identified. The biggest threat for hydrogen could in fact come from an unknown unknown: a factor that is completely out of the radars but with the potential the disrupt the sector.

3.2 Project developer point of view

3.2.1 SWOT results

STRENGTHS

- H2 projects can represent interesting investments for a large variety of companies
- Public support and current momentum are big strengths for project developers
- The capex is expected to decrease sharply in the future

WEAKNESSES

- Lack of H2 off takers for the produced H2 and lack of robust business model
- Lack of long-term vision for a project developer
- Lack of roadmap among industrial to trigger synergies
- Green H2 is expected to remain more expensive than carbon intensive solutions

OPPORTUNITIES

- Many promising technologies are under research
- The development of H2 is an opportunity for traditional companies
- A clear future would help the business
- The local producer will have an advantage
- Regulation can boost the development of H2 projects

THREATS

- H2 project developers will be in competition with other technologies
- Some regulations could jeopardize the profitability of the investments in H2 projects
- Green H2 projects profitability will be heavily dependent on a cheap supply of power
- Risk to bet on the wrong technology
- Political risk to lose interest in H2
- International trading of H2 could be a deadly blow to local producers

3.2.2 H2 projects can represent interesting investments for many industrials

Many actors of very different backgrounds have a clear interest in the development of a hydrogen ecosystem. We can list the following key categories:

- Hydrogen producers of all kinds (electrolysis, blue H2, other processes…)
- Hydrogen infrastructure project developers (pipes, storages, compressors…)
- Technology developers (fuel cells, electrolysers, high pressure storages…)
- Power and gas companies

For **hydrogen producers**, the interest is straightforward to understand. Moreover, thanks the low carbon requirements (see e.g. EU's taxonomy limiting the carbon intensity of carbon production to 3 kgCO2 per kg of hydrogen) and to the political push for hydrogen, they have high hopes of a significant growth market being in front of them.

For the **gas network operators and developers**, hydrogen is notably seen as a way to counterbalance the phasing out of natural gas. With hydrogen, the current gas network has an opportunity to transport carbon neutral gas and can therefore be part of the solution to deliver a climate neutral energy system.

For **technology developers**, the current enthusiasm is the opportunity to develop technologies that could later be sold worldwide. The political and financial support can enable some to accelerate the development of their technologies with R&D plans and financial support for early industrialization.

For **power and gas companies**, H2 production can become a significant share of their sells. For the gas industry, blue H2 is a very interesting way to sell "carbon neutral" natural gas. On the other hand, electrolytic hydrogen will require more power production and therefore more volumes for the electricity industry. In specific places, the additional power consumption needed to match the H2 strategy is a strong argument for new investments in carbon neutral power generation and in the electricity infrastructure at large.

For **RES project developers**, depending on the business models used, H2 could be a very interesting hedge against low power prices (as electrolysers are expected to consume power when prices tend to be low or even zero). Power production companies could also become H2 producers enabling them to optimize jointly their power sales and consumption. For such companies, H2 could bring diversification of revenues. This hedging potential provided by electrolysis to RES project developers has been explored by Energinet in its publication *PTX IN DENMARK BEFORE 2030 -Short term potential of PtX in Denmark from a system perspective*[43]. They found out that for low weighted average power prices, electrolysis could be an interesting hedge.

[43] (Energinet, 2019)

Many actors can have financial interest in the development of hydrogen system: hydrogen project developers, engineering companies, power and gas networks, power and gas utilities, RES producers…

3.2.3 Nevertheless, the big question is the potential lack of off takers

For hydrogen project developers, the most difficult question can be formulated as follow:

"Who will buy and use the hydrogen I produce?"

Currently hydrogen is produced specifically to supply a need for H2 feedstocks in specific industries. H2 projects are developed jointly with the corresponding offtake to match a certain level of demand. This was the case for concentrated H2 producers to supply industry and it is still the case for specific electrolytic projects designed to supply local refuelling stations.

Hydrogen is not a widely traded commodity where producers and consumers only interact through market prices, and it will most likely not become one in the absence of a large-scale cross-border infrastructure. As a result, hydrogen project developers must secure agreements with specific hydrogen off takers, at least in the early stages of the transition.

Hydrogen producers cannot mimic the biomethane business model. Indeed, biomethane business model is based on the possibility to inject the production into the gas network at tariffs reflecting both the energy sold and the "low carbon" dimension of biomethane. Moreover, those tariffs are very often fixed by the regulation, so that biomethane producers do not have to contract purchase agreements with consumers or to face market volatility. Unless considering blending into the gas network, this cannot be transposed in the case of hydrogen for the moment given that no publicly available hydrogen network exists today and that very few H2 demand exist besides large concentrated industrial off takers.

No robust profitable and scalable business model has emerged for the moment for hydrogen project developers.

Hydrogen is neither a widely traded commodity nor is it alike biomethane that can be injected directly in the gas network. Therefore, the hydrogen project developers must ask themselves who they plan to sell their production and they need synchronise their productions with the expected hydrogen demand.

3.2.4 The cost and the long-term visions are important subjects as well

A key element to develop more production assets will be the capacity of technologies to supply hydrogen at costs low enough to induce a profitable value chain. The project developer's profitability will rely on 4 important pillars:

- Get technologies with low and decreasing costs: the CAPEX component of H2
- Ensure cheap power supply for the functioning hours of the electrolyser: OPEX component of the cost of H2
- Have a number of full load hours as high as possible
- Get a good price for the hydrogen produced

As far as CAPEX are concerned, **projections predict a sharp decrease of the CAPEX in the coming years** with learning rates up to 18%. The CAPEX for alkaline electrolysis can drop from a current 1200 $/kW to 230$/kW in 2030 according to McKinsey's estimations in its study for the Hydrogen Council[44]. Other sources have similar predictions. ((Energy Transition Commission, 2021), Bloomberg NEF publications, etc). Those projections are nevertheless taking the underlying assumption of a scale-up of industrial production of electrolysers to benefit from the learning curve. Therefore, a growing demand for those goods is required to drive down the cost. Such a rapid increase in installed capacities of solar and wind was observed worldwide in the past few decades, but nothing ensures that the same thing will also happen for electrolysers. The current low production cost of electrolysers in China, as stated by Bloomberg NEF ((Agora, 2019) (page3)), are sources for optimism.

[44] (Hydrogen Council - McKinsey & Company, 2021)

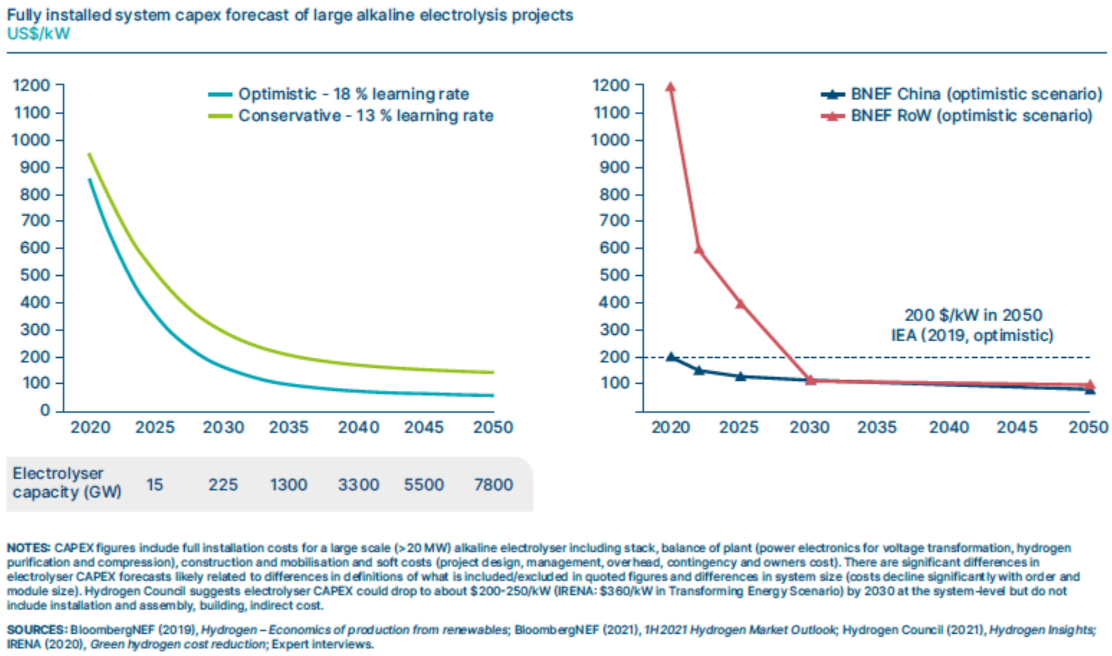


Figure 15: CAPEX projection of big alkaline electrolyser projects. (Energy Transition Commission, 2021)

As far as the OPEX component of the cost is concerned, it will be decisive for project developers to have access to low-cost renewable electricity to run electrolysis plants. In addition to the cost of RES, electrolysers will also need to extend the number of full load hours as much as possible to take the most benefits from their investment. The number of hours at low or zero electricity prices will have a great impact on electrolysis profitability as well. However, other flexibility solutions will be in competition for power purchases during those hours. Even in scenarios with high RES integration, the natural gas marginality is expected to remain the main “price maker” on the market. Hence natural gas and CO2 prices evolutions must be taken into account. Another solution would be for the project developers to purchase the required power with a portfolio of PPAs (Power Purchase Agreement) providing power with as much regularity as possible. Nevertheless, PPAs agreements’ prices will be heavily correlated to electricity market prices and will therefore be impacted by the marginal prices of electricity (driven today mostly by natural gas and CO2 prices).

The total production cost of green hydrogen is expected to decrease by up to 62% in 2030 according to McKinsey’s projections[45]. With those projections, green hydrogen could be competitive with blue hydrogen in 2030. In the long term (2050 and after), the 3 main hydrogen production methods could even have similar costs (without including specific CO2 taxation) [Figure 16].

Given that green H2 is expected to remain more expensive for a long time, some kind of support will be required when green H2 is in competition with grey or blue. Fortunately, the green H2 projects can

[45] (Hydrogen Council - McKinsey & Company, 2021)

be adapted to small local production needs whereas grey and blue H2 are only relevant in big consumption hubs. Two separate markets can therefore develop in parallel.

The absence of common roadmaps to produce synergies between industries working in H2 technologies has been identified by some experts as an important obstacle to the development of the sector and to the cost reduction of the technologies.

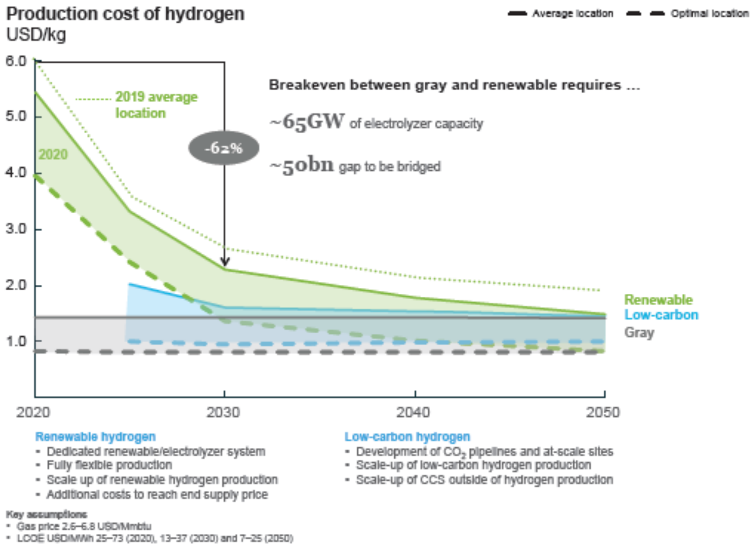


Figure 16: Hydrogen production costs by production pathway (Hydrogen Council - McKinsey & Company, 2021)

The lack of long-term vision for the project developers (both in the CAPEX and the OPEX component of the cost) could deter many of them from risking costly investments in H2 productions. Moreover, if they are certain that the cost will decrease rapidly, they are strongly incentivised to postpone their investments if they do not receive a strong counterpart.

The development perspective for project developers will strongly depend on the **cost reduction perspectives and the long-term vision they can have for their investments**. Some kind of support can be necessary given that green H2 is expected to remain more expensive. Finally, the perspectives of a sharp cost reductions could incentivise the project developers to wait before investing, delaying the pace at which the learning curve is run through.

3.2.5 Many elements are sources of enthusiasm

3.2.5.1 Many promising technologies are emerging

Currently, many promising technologies are emerging. As the market is still at an early stage, all the approaches can wish to have large growth potential. New emerging production technologies can be developed and compete with the current H2 productions processes by providing alternative business models.

In electrolysis, many concurrent technologies are still competing to become the best techno-economic solution with very different characteristics in terms of efficiency and flexibility (Alkaline, PEM, SOEC)

Pyrolysis processes for example could enable the production of H2 with biomass with the co-production of solid carbon that can be valorised in other applications as a feedstock material.

Many opportunities for project developers exist in this growth market still in an early stage. This is likely to boost innovation and reduce the costs of H2 technologies. However, **not having yet a dominant technology can be a two-edged sword for project developers who adapt their business model to a given technology**. Indeed, they face the risk that their technology remains marginal compared to another one that would be widely adopted and therefore would benefit from strong cost reductions.

The market for hydrogen project developer is very attractive and has a strong growth potential. No clear business model has emerged yet meaning wide range of opportunities but also many risks in a winner takes all model.

3.2.5.2 The development of H2 is an opportunity for traditional companies

H2 growth market is also an opportunity for more traditional companies that can use their technologies, competences and operational capacities to benefit from this growth market.

For the **gas infrastructure sector**, H2 is a powerful asset to continue using the current infrastructure (either via blending or via repurposing of part of the existing infrastructure). This is one of the very few options they have to avoid a brutal ending of their current business model in a context of decreasing demand for gas.

For many **traditional engineering companies** that design today equipment heavily reliant on carbon intensive fuels, the development of new technologies compatible with a carbon free energy is a matter of life and death under a carbon neutral constraint. Many sectors are impacted like aircraft engines, gas turbines, heavy duty engines etc. The emergence of H2 technologies will reshuffle the cards and new market leaders can emerge. For example, General Electric[46] is willing to produced H2 compatible turbines by 2030.

Oil and gas majors also have an interest in the development of blue H2. On the one hand, blue H2 could represent a strong gas demand with long term perspectives, on the other hand, those companies have the experience of offshore gas plants and could play a new role in the CCUS sector. For example, Equinor Shell and Total Energies are investing in the Northern Light project whose goal is to develop the first CO2 transport and storage network.[47]

For many companies, the development of H2 solutions can be a strong source of future growth.

[46] https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines
[47] https://northernlightsccs.com/

3.2.5.3 The local producers will have a clear advantage

Given the technical difficulties and costs related to shipping hydrogen in the early stages of the emergence of the hydrogen ecosystem, local producers will have a clear advantage. Moreover, the local production of H2 fits in the political narrative, willing to stimulate the local economies and labour markets.

Small green H2 productions will also have a great advantage compared to the large-scale SMR and ATR facilities that require strong gas infrastructure and that are only relevant to supply high hydrogen demand of big industrial clusters. For isolated H2 demand, small electrolytic H2 projects may well be better suited.

The absence of a real hydrogen network could very well happen to be an opportunity for small green H2 projects who will not be in concurrence with traditional SMR and ATR systems for the small local demands.

3.2.5.4 Natural technological switch is expected for some producers

For carbon neutral project developer, the rising trend of CO2 prices will naturally boost their technologies compared to carbon intensive technologies. According to McKinsey's projections[48], both green and blue hydrogen projects are more competitive than convention grey hydrogen in 2040 (with a CO2 price at 150 $/tCO2). For some experts, a 100€/tCO2 carbon price would be the milestone triggering a switch from grey to blue hydrogen for new projects. This evolution will require no political support in addition to the EU ETS price evolution. The phase out of currently grey H2 facilities is a different subject as it implies the destruction of an existing capital.

[48] (Hydrogen Council - McKinsey & Company, 2021)

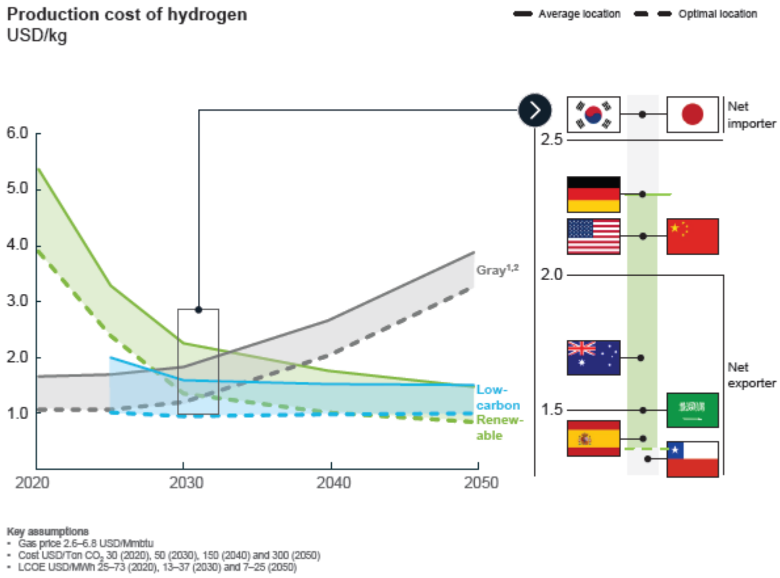


Figure 17: Production cost of hydrogen (USD/Kg).
The plain line corresponds to the average location and the dotted line to an optimal location (Hydrogen Council - McKinsey & Company, 2021). The price cost driven switch from grey H2 to blue H2 is expected around 2030 with a CO2 price at 50 USD/tCO_2

Carbon price growth is likely to trigger the end of new grey H2 projects, as they would be less competitive than bleu H2 projects.

3.2.6 Regulation can play an important role

Although many expect hydrogen to play an important role in the energy system to reach the carbon neutrality constraint, many highlight that **an appropriate regulatory framework can act as an important catalyst**. In the other hand, a **poorly design regulation is seen as a potential risk for the hydrogen sector**.

3.2.6.1 Some specific regulations can be beneficial to H2 projects

Regulation principles and political measures targeting carbon neutrality or pollution reduction can be the catalyst needed by the hydrogen sector to fully start-up its development.

More than 20 countries have already announced **sales bans on internal combustion engine vehicles** before 2035[49]. The mobility market will hence open to alternative solutions that are currently less competitive than classical fuels. This is an opportunity for the H2 value chain to develop clean mobility solutions in the short term.

[49] (Hydrogen Council - McKinsey & Company, 2021)

Natural gas phase out policies are also strong catalysts to hydrogen development. New solutions will be needed to replace the current applications of natural gas, either in the industry and the heating sector. Even though massive electrification takes the lion's part, the specific issues implied in terms of security of supply will create opportunity for H2 systems.

The recognition of a form of certification of the green character of H2 molecules can enable the producer to get these at premium prices compared to carbon intensive solutions in places where the two technologies are in competition in the same hydrogen network. Little by little, this mechanism could enable green H2 to replace conventional H2 production in consumption hubs even though the costs are higher.

3.2.6.2 Poorly calibrated regulation could slow down H2 development or even prevent any investment

A poorly calibrated, too ambitious or a frequently-changing regulation is a risk that the sector must face. As the business models are fragile at the early stages of the emergence of the hydrogen ecosystem, the impact of some measures can be very important for the profitability of H2 projects.

The **additionality principle**, designed initially to make sure that the pace of electrolysers development follows the pace of RES capacities, is seen by many stakeholders as an important threat to their business, notably because of the different build-up times for RES projects and electrolysis projects.

Many actors also fear that early **unbundling rules** would complexify their business models, reduce the financial interest of infrastructure investments and slow down the development of projects. Given the uncertainty of H2 production project profitability, one should be very careful when constraining the producers too much.

"H2 regulation must be adapted to an emerging system"

Technology-specific regulations can also represent a high risk for project development. A carbon content-based regulation is much more transparent and the long-term impact much more predictable for the project developers.

Regulation on H2 is two edged sword. On the one hand it can boost the sector but in the other hand it can induce uncertainty and reduce the appetite for long-term investments.

3.2.7 The project development will depend on the long-term perspective to have cheap power supply

3.2.7.1 Project developers will face a commodity-risks

The H2 projects will consume a lot of energy: electricity to fuel the electrolysis or methane for the SMR and ATR facilities. Rising prices of gas and power could erode the viability of these emerging business models. The 3 main commodities that need to be closely looked at are electricity, gas and CO2.

Electricity

High electricity prices could threaten many electrolytic H2 projects. To reduce the risk of power markets exposure, H2 projects have several options among which:

- Have their own power supply with dedicated RES production.
- Have a long-term supply of decarbonised electricity through power purchase agreements (PPAs). However, PPAs' prices will follow the trends of the power market. High long term power prices will tend to increase the PPA costs for H2 developers.
- Use financial hedges against power market price volatility.

The real impact of electricity prices on green H2 projects will depend on the business model chosen by these projects and the structure of electricity sourcing options. If electrolysers only work in periods of low-prices (RES marginality), then electrolytic H2 projects are likely to be less impacted.

Natural gas

The impact of a rise in natural gas prices is likely to impact all the H2 projects. For the grey and blue H2, the relation will be direct as methane is the main variable cost component for H2 production.

But a raise in natural gas prices would also trigger a raise in electricity prices as long as the marginal power producer remains a gas-fired power plant. Those higher prices would nevertheless not occur for the hours where renewable energies are marginal producers. The impact one green H2 is therefore difficult to assess and will depend on the business model chosen for the electricity supply of electrolytic H2 projects.

CO2 prices

Among the commodity prices, CO2 is the one with the most certainty about its long-term growth.

In the short term, an increase in CO2 prices will incentivise a switch from grey to blue H2. Green H2 could also benefit from the phase out of old SMR and ATR facilities but the market signals will not be sufficient, at least in the short to medium term. However, as for the gas prices, a raise of CO2 prices will have a direct impact on electricity prices for some hours. As explained in paragraph 3.1.3.6, a growing CO2 price could have a greater impact on green H2 than on grey H2. Evolution of CO2 prices could also impact the competition between hydrogen and other carbon free solutions like Biomethane that could be less impacted by CO2 prices.

The raise of commodity prices is a risk for all H2 project developers. For green H2 project, this risk can be mitigated by defining appropriate business models. However, the actual impact of electricity, gas and CO2 prices on green H2 is complex and requires careful analyses.

3.2.8 H2 project developers will be in competition with other technologies

New H2 projects and especially carbon neutral project developers will face an important competition. This competition will be reinforced given that everyone wants a share of the H2 market. But the most important competitors to low carbon H2 projects could lie outside the H2 ecosystem.

Competition with fossil energies

The first competitor that is foreseen for H2 are the fossil fuels currently widely used in most of the energy applications explored for H2. Currently fossil fuels remain cheaper than H2 but a decrease in fossil fuel prices could postpone the switch to H2 usages without appropriate price signals or regulatory frameworks.

This competition between H2 and fossil fuels concern all the sectors:

- **Mobility** with conventional gasoline and gas for vehicles.
- **Industry** where methane and oil-based products remain at the core of many processes.
- **Flexible power generation** where gas-fired power plants play the major role.
- **Long term storage** which is currently done by underground gas storage.

Competition with other power focused technology to access low-cost electricity prices

Green H2 project developers will also be in competition with other companies to have access to the periods of cheap electricity prices. This competition for those hours will naturally increase the prices of electricity by increasing the demand and reduce the number of hours at very low prices.

We can list many examples:

- Electric vehicles whose large deployment is widely expected among experts in the coming years.
- Batteries for short term storage.
- Pumped hydro storages.

Competition with alternative sources of low carbon commodities

Alternative sources of low carbon commodity are also strong competitors for hydrogen. Indeed, in many applications, H2 will not be the cheapest decarbonised solution. The alternatives could be:

- Bio gas or biomethane for industries.
- Biomethane for vehicles, public transportation and heavy mobility.
- Biomass for some heating applications.
- Direct electrification of industrial processes.
- Electric mobility.

Competition with CCUS to decarbonise some industrial processes

CCUS is another alternative to the usage of a carbon neutral solution like green or blue hydrogen. Instead of replacing their machines to enable H2 based processes, industrials can also reduce their current CO2 emissions with CCUS technologies. By doing so, they would keep the same energy supply mix and have only to apply marginal changes to their processes. CCUS can be an interesting solution for industrial clusters where the carbon emissions are concentrated and where a unique CO2 infrastructure could handle the CO2 treatment for multiple factories.

The deployment of blue H2 would trigger the development of such CO2 infrastructures and could create momentum in the industry with a self-inhibiting effect on H2 perspectives.

Competition with outsiders not yet identified

Besides the competitors already identified above, the most threatening competitor for H2 project developers could in fact be the ones that are not yet clearly identified.

Among the potential game changers, **Small Modular Nuclear Reactors** are quoted by some experts as the technology with the highest disruption potential. This new nuclear technology currently benefits from a strong momentum in North America with large investments in some companies willing to produce their first reactors in a couple of years, and in Europe where France is considering investing in this technology under the “France 2030” initiative. This new generation of reactors could be suited to the supply of heat and power in industrial clusters or even in large factories with a dedicated reactor to match the energy needs. It could also provide baseload power, reducing the need for storages and flexibilities compared to a situation with extra RES capacities. The possibility to also obtain power generation flexibility services from small modular reactors, able to handle the mid-term flexibility needs induced by the variability of wind generation, is a potential game changer. Finally, this solution would be much easier to handle than conventional nuclear and could be deployed in many countries with low barriers to entry.

New generation of conventional nuclear reactors could also resolve some bottlenecks on the power sector, reducing the market share of flexibility of which hydrogen is willing to take a portion. The deployment of conventional nuclear could also enable a large supply of carbon free electricity to supply electrolysers with unmatched load factors compared to renewable energies. Conventional nuclear could hence boost H2 projects for many of its applications.

H2 project developers will face a fierce competition against many alternatives to green H2:

- Fossil energies
- Alternative sources of carbon free energies (Bio methane, bio fuels, biomass, electrification…)
- Competition with alternative carbon free model (CCUS in industries per example)
- Competition with outsiders not yet identified (Small modular reactors could be one of those)

3.2.9 For the project developer, the industrial risk and the political risk remain strong

Two kinds of risks will remain for project developer, regardless of the hedging measures they can take.

Risk of betting in the wrong technology

The first risk to face is the **risk of betting on the wrong technology**. This risk is inherent to a new emerging sector where multiple technologies exist but no clear dominant solution prevails. For a project developer, there is a clear interest in betting in the technology with the most widespread early adoption to benefit from the learning curve effect. On the other hand, if the technology chosen is left behind by the industry, then the contribution to the learning curve would be halted and the cost decrease would be much less than expected, regardless of the intrinsic qualities of the technologies.

Political risk on H2 perspectives

The second risk is **the political risk to lose the current support**. As discussed above, the H2 technologies development will strongly depend on some kind of support to kick-start the H2 ecosystem. In particular, **most of the additional applications of H2 are only relevant in the context of deep decarbonisation objectives**. In the case where this carbon neutrality constraint in 2050 is relaxed, the relevance of additional H2 usages could be questioned. We can imagine that the current 2050 constraint could be postponed to 2060 or later for political or financial reasons. This would be a hard hit for H2. More fundamentally, with the current characteristics of H2, those new applications for H2 are completely dependent on the collective effort to reach carbon neutrality. If this ambition came to fade, then the prospects for H2 and green H2 in particular could collapse.

If there is more to lose than to win no one will take the bet. Usually, in such a situation, we would expect very high potential benefits for those who take the risk and success. Nevertheless, high margins are seen very unlikely for H2 project developers.

3.3 Consumer point of view

3.3.1 SWOT results

STRENGTHS	WEAKNESSES
• Enable the decarbonisation of some final usages • For companies it is a way to convey a "green image". • Can enable off-grid business models • Can bring more value than other green solutions	• Cost will be much higher for the consumers • Lack of long-term vision
OPPORTUNITIES	**THREATS**
• Clear opportunity to start-up the H2 sector by relying on current H2 consumers • Some regulation mechanism can trigger improve the profitability of industries switching to H2 • H2 market and importations could enable cheap supply of H2	• The question of who will pay for the transition has yet to be answered • Public acceptance and security are key and could represent an important threat if poorly managed

3.3.2 For the consumers, hydrogen is likely to represent only little advantages

From a consumer point of view, a switch to using hydrogen presents only very little advantages.

The main advantage: possibility to decarbonise the final usage

The whole point of switching from fossil fuels to H2 (or from grey H2 to low carbon H2) is for the consumers to be able to reduce their carbon footprint. **For companies, this can provide a strong corporate branding opportunity of being committed to carbon neutrality or being a "green" company, which is becoming an important factor in consumers' decision-making process.** Such companies may be willing to pay a higher cost to reduce their emissions to the following advantages:

- Improve its image for its clients and more general its public image.

- Attract investors willing to target their investment toward carbon neutral activities (see e.g. the efforts to establish a taxonomy in Europe)
- Ensure a future-proof business model.

A switch to hydrogen may also be considered as a solution for individuals willing to reduce their carbon footprint.

Security of supply or off-grid solution

The mid- to long-term "power storage" that enables a system with RES production + electrolyser + storage + fuel cell can be appealing for some very specific industries willing to be more independent from the grid. There are also strong aspirations of some individuals to become energy self-sufficient (or in autarky). Finally, H2 storages coupled with fuel cells can play the role of back up electricity production and replace the conventional diesels back-ups. However, H2-based backs up will have the drawback to be very capital intensive which is one of the most discriminant arguments when considering a backup solution. For example, in India, fuel cells are used to ensure uninterruptible power for telecom towers[50].

H2 can bring more value than other carbon neutral solutions for some applications

If hydrogen cannot compete with fossil fuels in terms of services they bring to the consumers, **H2 can nevertheless be a strong challenger of some other carbon neutral usages**.

In mobility for example, the electric mobility presents the major drawback of a very slow refuelling capacity unless one has access to supercharging infrastructure. This characteristic of electric vehicles completely changes the approach to mobility. However, **H2 mobility presents usage characteristics very similar to fossil fuel mobility**. In mobility, H2 have a decisive advantage compared to electric mobility with an **additional use value**.

In most cases, H2 usage represent a loss of value

All the argument above being put apart, using H2 instead of another fuel is likely to induce no real advantage for a consumer. On the contrary, the usage of hydrogen comes with very important drawbacks:

- High transition cost to accept H2 in the industrial process or in residential appliances.
- High H2 supply cost.
- Complexity to handle H2 and security issues.
- Low use value (or at most the same service) compared to fossil fuels or other carbon neutral fuels.

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[50] (IEA, 2019)

Thus, in the consumer point of view, and given the current state of knowledge, hydrogen consumption probably implies more cons than pros.

3.3.2.1 Higher costs

The high expected cost of H2 – at least in the foreseeable future – will be the biggest default of hydrogen for the consumers. In this regard, it is important to break down the H2 usages in two categories:

- Usage as a **feedstock** where H2 is required. The competition will therefore be between different H2 sources.
- Usage as **energy carrier**. For this usage, H2 is far from being the only carbon-neutral solution and H2 is relevant only if it can be cheaper than other solutions for the same usage. This role is currently played by other energy sources, often carbon intensive and often at low cost.

For many experts, the projected high costs completely prevent the use for **heating applications in households**. Indeed, space heating requires a cheap and widely available source of energy, characteristics that H2 will most probably not have. This is sometimes referred to as the “champagne” argument.

For industrials, changing their productions lines, furnaces and machineries and switch from fossil fuels to hydrogen represents a high cost to pay for no additional services provided by hydrogen compared to fossil fuels.

Among the energy applications, H2 will be relevant only in cases where the energy usage is associated to a very high value creation that could justify the use of an expensive commodity. Industries with high added value are natural targets (cosmetics, high end chemicals…). In the other side of the spectrum, industries with low added value or industries where the added value per consumed energy is low, will face much more difficulties to switch to H2 a reasonable cost.

For example, in the iron industry, the technology DRI-EAF (Direct Reduction Iron – Electric Arc Furnace) with H2 used in the DRI process could reduce the CO2 emissions up to 95% with a cost of avoided CO2 emissions of 140€/tCO2 but required investments are very high[51]. Thyssenkrupp estimated that in order to replace its current 13 million tons of iron production with the new DRI-EAF technology, it would cost 10 B€, (i.e. 770€/ton of iron). This investment is to be compared with an iron price around 400€/ton of iron (subject to market fluctuations).

The prospective committee of the French energy regulator CRE[51] concluded that given the high cost to switch to H2 the iron production, no business model currently exists. According to the CRE publication, the adoption of H2 technologies will depend on the followings:

- CO2 price on the EU ETS.

[51] (Comité de prospective de la CRE, 2021)

- Carbon adjustment mechanism at the borders to protect European industry.
- Willingness of the consumers to pay a premium for low carbon products.
- Other forms of regulation to split the transition costs between producers, consumers and tax payers.

3.3.2.2 Lack of long-term vision

The lack of long-term vision is also identified as a barrier to private investment from a consumer point of view. Indeed, potential consumers cannot estimate the future supply cost of H2 that they would face and therefore build their business model accordingly. For industrials or small independent consumers, the switch to H2 processes and appliances is a gamble if no hedges are taken, with heavy potential losses and few upsides. A long-term supply of H2 at guaranteed cost would be decisive to incentivise the conversion to H2 solutions.

To compensate for this lack of long-term vision that could prevent the private sector to invest, clear, stable and long-term objectives given by policy makers are a very important. The inclusion in the "Fit for 55" package of a 50% target for "renewable fuels of non-biological origins" in the share of hydrogen fuels used in European industry by 2030[52] is an important element in that direction.

Given the lack of long-term vision, the switch to H2 is very risky for the consumers. Long term supply of H2 at guarantied cost would greatly simplify their business model. The policy maker can contribute to clarify the investors perspectives by providing clear long-term targets.

3.3.3 There is a clear opportunity to start-up the carbon neutral hydrogen by relying on the switching of current H2 consumers

The current usages of H2 are probably the most favourable places where to start up using carbon-neutral hydrogen from a consumer point of view. Indeed, the switch to carbon-neutral H2 can imply additional production cost but will not require any investment to change the processes themselves.

As a result, the current consumers of carbon-intensive H2 are the most likely to initiate the adoption of other H2 supply sources and to start-up its production with significant needs. This is all the more true since those consumptions are feedstock consumptions, with no alternative to H2. The competition will be between the various carbon-neutral H2 solutions. In that context, blue H2 will have a strong advantage compared to other H2 production processes, as only little adaptation is required to switch

[52] https://www.euractiv.com/section/energy/news/eu-green-hydrogen-plans-hailed-as-true-game-changer-by-industry/

from grey to blue H2, even if the sustainable nature of blue hydrogen can be questioned, notably due to methane leakage.

3.3.4 Other factors can help the transition

Other factors can help the transition to H2 usage for consumers, even though the costs projections indicate a high cost for H2 appliances. Those factors are:

- Carbon contract for difference mechanisms.
- Liquid Markets of H2.
- Long term certainty on the supply of H2.
- Importations of H2 or of H2 based productions (like ammonia or methanol).
- Research and development efforts.
- Prescriptive regulations.

Carbon contracts for difference

This system is described in paragraph **Error! Reference source not found.**. In sectors where H2 is the unique decarbonisation solution currently expected, this system can be the catalyst to enable the transition. Some interrogations remain to determine who will support the cost of this mechanism.

Liquid market for H2

A liquid H2 market would enable a rapid cost reduction of energy supply among the producers in competition (and prevent monopoly behaviours). With a given demand curve for H2, the reduction of production cost will increase the amount of production and reduce the price, increasing both the producer surplus and the consumer surplus.

Long term supply of H2

Long term certainty on the supply of H2 at prices decided in advance could enable potential consumers to secure a profitable business model with carbon-neutral energy.

Importations

Importation of cheap H2 (see paragraph 4.2) from other countries could represent a very important opportunity for local H2 consumers. Nevertheless, it also entails the risk to import transformed H2 based products instead of H2, jeopardizing the local industries (e.g. refineries). For example, it may make more sense to import directly ammonia rather than importing green H2 and transform it back into ammonia.

Efforts in research and development on new processes

Research on new industrial processes is essential to find new cost-effective ways to use green H2. In this regards, European IPCEI (Important Projects of Common European Interest) is a powerful system to share knowledge and accelerate the development of green H2 consumption.

Prescriptive regulations

Finally, prescriptive regulation like natural gas bans can be very beneficial for the development of H2 based consumptions. Nevertheless, such measures can induce cost of avoided CO2 far above what an optimal capital allocation would have permitted and important frictions for those forced to change their business model.

3.3.5 "Who will pay for the transition?" is a tricky question

Many consumers cannot afford to pass through the rising cost of H2 supply on its clients. For example, ammonia is mostly used for fertilizers used in the agriculture. But agriculture is a sector under pressure with a lot of farmers already struggling for profitability. A rise in fertiliser costs could be a terrible blow for them. More generally, there is today only little willingness to pay more for a product with less carbon emissions impact.

In any cases, industrials will need a form of protection to undergo the cost surplus induced by H2 usage. The two mechanisms currently under discussion are carbon contracts for difference and carbon taxation at the borders of the EU. Nevertheless, none of these will cope with the structural production cost increase in the industry and its macro-economic impacts (see paragraph 3.1.4.4).

3.3.6 Public acceptance and security are important

Public acceptance and high security standards will be the keys of the deployment of H2 usages. For the industrial usages, the high security requirements will induce additional costs but can be managed. For usages closer to the final user this is a more complicated question.

A lethal accident with a lot of mediatic echo has the potential to shift the public opinion against the usage of this new technology. For example, the memory of the Hindenburg's accident has still an impact on the way some Germans apprehend H2 risks. More recently, the explosion of a H2 refuelling station in south Korean provoked a rejection movement against H2 for mobility[53].

[53] https://www.reuters.com/article/us-autos-hydrogen-southkorea-insight-idUKKBN1W936A

4 A closer look to specific H2 subjects

4.1 The role of blue hydrogen and of hydrogen blending to kick-start the hydrogen ecosystem

4.1.1 What is blue hydrogen

The appellation blue hydrogen designates the classical production of hydrogen with natural gas (Steam methane reforming or Autothermal Reforming), combined with a carbon capture and storage system (CCS). With this system, hydrogen is produced with natural gas extracted from underground and the CO2 is injected back underground, with a theoretical zero additional CO2 rejected into the atmosphere.

The core of the blue hydrogen technology relies on the CCS. The following steps must be covered by the CCS technology brick:

i. Capture of the CO2 from the process: The fumes must be treated to prevent the CO2 from flying away in the atmosphere. A first step consists in separating CO2 from other gases before compressing it.
ii. Transport of the CO2. If no application exists next to the blue hydrogen facility, the CO2 must be transported to a new industrial site where it is used, transformed or stored.
iii. Storage of CO2 or utilisation in another process.

4.1.2 Strengths of blue hydrogen

The development of blue H2 systems can have several advantages among which:

- Usage of existing SMR and ATR facilities.
- Opportunity to kick start the hydrogen economy at contained costs.
- The switch from grey to blue can be drive by an efficient CO2 price and will require no subsidies.
- Opportunity to develop a CO2 economy.

Usage of existing SMR and ATR facilities

The first and indisputable strength of blue hydrogen is its capacity to provide a hydrogen supply that is expected to be just slightly less competitive than grey hydrogen. Moreover, we could rely on the already existing SMR and ATR facilities and adapt them to enable carbon capture. By doing so we reduce drastically the needs for investment in new production capacity and we do not change the current hydrogen ecosystem. Hence, blue H2 is by far the most cost-effective way to **decarbonize the current hydrogen production**. Nevertheless, in the medium to long run, plants will need to be renewed and the question to build new blue hydrogen facilities will inevitably be raised.

Opportunity to kick start the hydrogen economy at contained costs

As it is heavily based on an existing technology and only requires limited additional technology advancements, **blue hydrogen can be a bridge toward green hydrogen**. Indeed, today the development of green hydrogen suffers from two main issues:

1. The production cost is very high for many usages.
2. There is very little demand for green hydrogen, and the future expected demand is very uncertain.

In its *Strategy for a climate neutral Europe*[54], The European Commission acknowledges the role of blue H2 as a mid-term bridge to H2 economy by ensuring carbon emission reductions:

> *"**In the short and medium term, however, other forms of low-carbon hydrogen are needed**, primarily to rapidly reduce emissions from existing hydrogen production and support the parallel and future uptake of renewable hydrogen."*

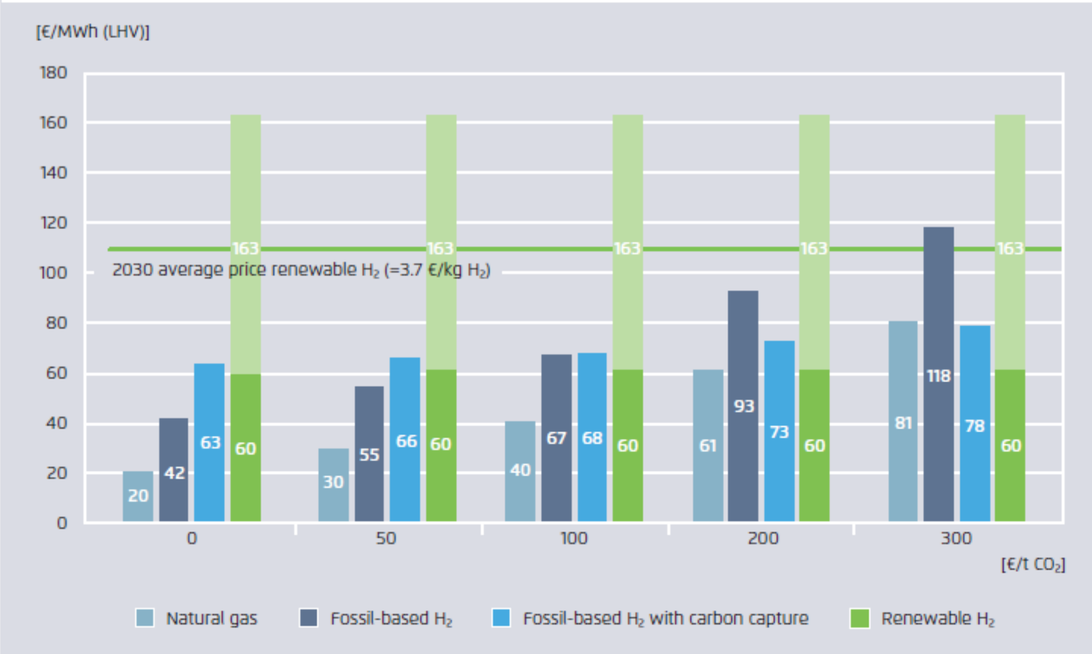
Those two issues are scarecrows for any industrial business willing to decarbonize its production and wondering whether hydrogen could be an answer. Blue hydrogen can let the demand side of the hydrogen economy develop and attract new hydrogen off takers in the market, benefitting from cheap, low carbon hydrogen.

If the demand for carbon neutral hydrogen is robust, then the market will incentivize other sources to develop. Green H2 could have here the opportunity to develop itself if the cost reduction perspectives are met (a regulation in the favour of green H2 could also be considered in that case). If those conditions are not met, then blue H2 would have played a role of protection against misallocation of capital.

The switch from grey to blue will be CO2 driven and will require no subsidies.

We stated above that very little additional investment is required to switch to blue hydrogen. In fact, very little government intervention and subsidies are required as well. Those investments will be triggered naturally once the CO2 price will reach a certain threshold. The industry will bear by itself the cost of the investment (Figure 18).

[54] (European Commission, 2020)



Agora Energiewende & Guidehouse (2021)
Note: For natural gas, a price of €20/MWh is assumed. The capture rate for fossil-based H_2 with carbon capture is assumed to be around 75%.

Figure 18: Impact of carbon pricing on the economics of hydrogen production pathways, 2030 (Agora, 2021)

Opportunity to develop a CO2 economy

In addition to the hydrogen economy, blue hydrogen could also be the **kick starter of the CO2 and CCUS economy**. Indeed, blue H2 will require the construction of CO2 facilities to concentrate the CO2 from the fumes and CO2 networks to transport the CO2 elsewhere (either to store it or to use it in other processes). This network could be used by other industries of the industrial areas that have process with large carbon dioxide emissions, even though those industries have nothing to do with hydrogen. Blue hydrogen could have a leverage effect on the decarbonisation of industrial processes, even though those processes are not hydrogen based.

4.1.3 Major weaknesses

Blue hydrogen presents a number of drawbacks. In the following section we will discuss some of them:

- Persistence of the natural gas value chain
- Capture rate is not 100%
- The CO2 captured needs to be transported used or stored
- Risk of lock in effect

We keep the gas value chain and therefore all the emissions alongside this value chain

With blue hydrogen, **the carbon neutrality step is set after the industrial usage of hydrogen**. We therefore need the usage of a carbon intensive fuel (natural gas) extracted from the ground and we limit the impact of its usage by reinjecting the CO2 into the ground downstream in the process. It is very different from the green hydrogen approach consisting in not using carbon intensive component in the value chain at all.

The blue hydrogen value chain hence preserves the existing natural gas value chain which is heavily debated. Two majors' aspects are often listed:

- The usage of conventional natural gas incentivises the energy industries to keep on investing in this fossil fuel instead of orienting their investments to other energies with long term perspectives matching the carbon neutrality objectives.
- In addition to the downstream emissions due to the combustion of natural gas, more and more attention is given to the upstream emissions due to leakages in the gas networks and extraction processes.

The capture efficiency is debated

Even with the best capture technologies that we have today, the capture rate is not 100%. As a result, the blue hydrogen technologies cannot be considered as strictly zero carbon emissions. Those fugitive emissions are at the centre of the work done by Howarth and Jacobson[55] to assess impact of blue H2 on greenhouse gases emissions. This article led to heated discussions among scientists, experts and analysts on the way to account for future emissions and on the theoretical and actual capture rates of CCS. If some people consider this as a decisive argument against blue hydrogen, this position must yet be balanced:

- Direct CO2 emissions remain very low compared to grey hydrogen.
- The direct emissions are just one component of the total carbon footprint. And no technology can be considered today as completely carbon neutral if we take into account the whole life cycle analysis.

The CO2 needs to be used or stored

In order to be truly efficient, the blue hydrogen industries must be careful to what is done with the CO2 that is being captured. If stored, one must make sure that the CO2 will stay underground and will not leak from the storages.

In terms of storage capacities, experts say that the potential for CO2 storage in Europe is not a problem. The problem lies more on the legal ability to trade CO2 among countries and to store it underground without leakages. Moreover, the business model for CO2 storage is still unclear. If a company stores

[55] (Robert W. Howarth, 2021)

CO_2 today, benefiting from the EU ETS at current prices, how would be estimated the cost of a leakage in the storage many years after when the prices for CO_2 will be much higher? Furthermore, how will be financed the industrial installation of CO_2 storage in the very long term, given that they do not bring any value to the system ones they are full?

Risk of lock in effect

The lock in effect consist in the idea that if we use blue hydrogen as a bridge technology with the final objective to get to a hydrogen system relying mostly on green hydrogen, we face the risk to be locked in fossil fuel usages. The lock in could have two main reasons:

- If the hydrogen ecosystem is fully adapted to big blue hydrogen facilities, this could create barriers to entry to potential new players with very different technologies. Those barriers could concern the access to the network, the technical proprieties of the gas, or the market design used for the trading of hydrogen.
- If cost of green H2 does not reach the expected decrease, then no green H2 solution will ever emerge. Moreover, given that short term investment in hydrogen production will be dedicated to blue hydrogen, the learning curve of green H2 could be much flatter than it could have been with direct investment into green H2 technologies. However, as this would also impact the demand side of the early demand side of the market, it is very complicated to draw a clear conclusion (with blue H2, the short-term demand for carbon neutral hydrogen is expected to grow more rapidly in the absence of other support mechanisms). This concern has be raised by some experts and can by found in some papers (see for example (Ueckerdt, 2021)).

Finally, some could argue that in the situation where green H2 costs cannot follow the blue H2 costs, then having chosen blue H2 instead of green would have been a good allocation of capital decision.

4.1.4 Conclusion

Blue hydrogen could be a powerful opportunity to **decarbonise H2 production in the short term** and can play the role of a **bridge technology toward the green H2**. Nevertheless, its utilisation raises many concerns and has very little support. Many stakeholders ask to switch directly to green H2.

4.2 The role and modalities of hydrogen imports

If the local production of hydrogen is seen as the base case scenario for Europe, hydrogen imports from other countries could very well be an alternative solution to get cheaper prices to supply the domestic demand.

4.2.1 Requirements of hydrogen imports

The major prerequisite to consider hydrogen imports is to have the technical capacity to transport hydrogen on long distances and at reasonable costs. Among the solutions that are proposed, the most convincing ones falls under two different categories:

- Transport in hydrogen form (compressed gas, or liquid form)
- Transport of hydrogen under the form of another chemical (ammonia, methanol…)

Transport in hydrogen form

Three solutions seem to be adapted for long distance transportation:

Hydrogen pipelines. Hydrogen pipelines are efficient solution for the long-distance transport of gas as they enable the transport of large quantities with high flows. Nevertheless, the required infrastructure is rather expensive to develop if imports have to transit across Europe to reach consumption centres as costs depend on the distances to cover. The cost of pipeline transportation can become prohibitive if distances are too long or in the absence of repurposing options

High pressure storage in tanks. Another solution could be to compress hydrogen at very high pressure in tanks adapted to ships or trucks. This solution is technically complicated to implement for hydrogen given that the volumetric energy content of hydrogen at normal conditions is very low. The economics of this solution remains unclear

Liquid form transport. The last solution that is often listed is to liquify hydrogen to transport it on ships, mimicking the Liquified Natural Gas ecosystem. Owing to the physical proprieties of hydrogen, its liquefaction is a complicated process requiring extreme conditions of pressure and low temperatures. That is why this solution is expected to be very expensive.

Transport of energy in another hydrogen based chemical component

Two well-known forms are often quoted as relevant for long distance energy transportation: **methanol** and **ammonia**. This new imported chemical can be directly used as feed stock instead of local production of these chemicals (that uses local production of hydrogen). Another usage could be to use directly those chemicals as energy carriers instead of hydrogen or to add an additional step and to crack them back to hydrogen.

<0.1 USD/kg | 0.1–1 USD/kg | 1–2 USD/kg | >2 USD/kg

		Costs				
		Distribution		Transmission		
		0–50 km	51–100 km	101–500 km	>1,000 km	>5,000 km
Pipelines[1]	Retrofitted	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/Subsea transmission pipelines	N/A
	New	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/Subsea transmission pipelines	N/A
Shipping	LH_2	N/A	N/A	N/A	LH_2 ship	LH_2 ship
	NH_3[2]	N/A	N/A	N/A	NH_3 ship	NH_3 ship
Trucking	LOHC[2]	N/A	N/A	N/A	LOHC ship	LOHC ship
	LH_2 trucking	Distribution truck LH_2	Distribution truck LH_2	Distribution truck LH_2	N/A	N/A
	Gaseous trucking	Distribution truck CH_2[3]	Distribution truck CH_2[3]	Distribution truck CH_2[3]	N/A	N/A

1. Assuming high utilization
2. Including reconversion to H_2; LOHC cost dependent on benefits for last mile distribution and storage
3. Compressed gaseous hydrogen

Figure 19: Overview of distribution options. (Hydrogen Council - McKinsey & Company, 2021)

4.2.2 Strengths

Use of the most productive regions in terms of renewable power

Many regions seem much more gifted than Europe to provide low-cost renewable electricity thanks to their solar irradiation or wind characteristics. Some evaluate the possibility to produce H2 with solar power in North Africa, and transporting it through pipes until the Ruhr region. If those transport solutions are cheap enough, they can even be coupled to H2P plants (hydrogen to power) and be used as “long-distance electricity import” solutions. This could be an interesting way to get a **highly predictable base production of renewable power**. However, the viability of such a solution must be assessed with a cost benefits analysis and the low production cost of electricity must compensate the low efficiency of fuel cells. Another solution that has been mentioned during interviews is a value chain based on oxycombustion where CH4 and CO2 are exchanged between regions (electrolysis and methanation on one end, oxycombustion and CCS on the other).

Diversify the supply sources

The ability to import hydrogen can be a strong hedge against local variations in H2 production volumes and against H2 prices volatility. A steady and predictable supply of hydrogen, not correlated to European weather conditions like the one of local green H2, could have a strong value. Moreover, the cost associated to this international supply would be less correlated to EU power, gas and CO2 prices.

4.2.3 Weaknesses

High transportation cost

The biggest issue with long distance transportation of H2 is its cost. Regardless of the distance, all the H2 transport technologies remain today expensive compared to current energy transportations costs. The transport component of the imported hydrogen is expected to be significant.

The repurposing of part of the existing gas infrastructure could help to reduce the required level of investments.

If the new gas cannot be used under its form, a new step is required

If hydrogen is used transported under the form of ammonia or methanol for transportation, an additional step is required to transform those chemicals back to hydrogen (cracking) or to use them to produce methane. Direct usage of those chemicals as energy providers can also be considered but raises many concerns for hazardous gas like ammonia.

Is hydrogen import truly a good investment toward carbon neutrality?

Similar to what we explored in paragraph 3.1.3.6 about the true carbon impact of electrolytic H2, one can wonder if the importation of H2 is the optimal utilisation of renewable electricity or hydrogen produced abroad. In many places like North Africa where the power demand is high and very carbon intensive this argument has a big importance.

This should be balanced with the demand side development of H2-based processes in Europe resulting from those imports that could have a long-term worldwide impact.

We keep the same issues of energy dependence as before.

The imports of hydrogen have the drawbacks to keep a fundamental dependency on EU's energy supply. If this solution is chosen, diplomatic questions of long-term alliance with exporting countries will need to be raised. A more diffuse importation strategy with shipping from many different places would be much less subject to this strategic problem. However, it should be acknowledged that renewable resources are more distributed around the globe than fossil fuels like oil and gas, reducing the risk of a dependence to a limited number of powerful actors.

It will naturally be in competition with local production of methanol and ammonia.

If H2 is imported, then there is no reason that hydrogen-based products like methanol and ammonia, easier to transport than hydrogen, would not be imported as well. It would reduce the market share of EU chemical productions but also the market share of local H2 production.

4.2.4 Other business models are possible

The major competitor to hydrogen imports remains the local production of H2. Besides the argument of a potential prohibitive transportation cost, the local production of green H2 benefits from a strong political support.

Alternative prospective models can also be investigated. For example, a CO2-based market could be an alternative to hydrogen imports. In a CO2-based market, we keep using methane for part of the industries (and potentially also the power production). We therefore have both a demand for hydrogen and steady CO2 production. This model consists in the following steps:

- The CO2 emissions are captured and transported with pipelines to neighbouring countries with high-RES resources.
- The CO2 is then combined with green H2 produced with high efficiency through a methanation process. We therefore produce methane (main component of natural gas).
- The produced methane is exported back to Europe using the existing infrastructure.
- The methane is used in EU industries, notably via oxycombustion.

In this model, we therefore use both CO2 and methane as energy carriers to fuel the EU industries with renewable energy. Hydrogen is produced and transformed locally, solving the transport and storage issues. This model requires two main components:

- A CO2 infrastructure in parallel to the existing natural gas infrastructure.
- Efficient methanation facilities

5 Crossed vision synthesis

The paradox of hydrogen is that in the long term, the consensus is that hydrogen will be required to reach the net zero target. But when explored in details, hydrogen-based solutions seem to have in reality very few advantages for both the producers and the consumers.

On explication of this apparent paradox is that the **true value of hydrogen is to enable a net zero energy system**. However, there is **no direct associated value** besides the avoided climatic impact that could be the basis to construct a profitable business model for hydrogen producers and consumers.

To put it in a nutshell, hydrogen would most likely be an idea that would not emerge if not for CO2 emissions constraints or resource limitations As these constraints do actually exist, it is important to find out the best acceptable solution to meet decarbonisation objectives. In that perspective, H2 could be an important element but support mechanisms will be required or else the targets have only limited chances of being reached.

Main issue: mismatch of interest across stakeholders

In the long term, the consensus is that hydrogen will be required to reach a net-zero target. **There is therefore a clear systemic interest for H2 development in the context of a net zero strategy**. But when explored in details, **hydrogen-based solutions seem to have in reality very few advantages for consumers**. Indeed, for the consumers, H2 usage is not “game changer”. It will not provide to them new goods or services or reduce the current cost of those goods and services. In the contrary, it is very likely that those service will be of a lower value for consumers (given the difficulties to handle H2 compared to current carbon intensive solutions) and will cost more than the current existing solutions. The emergence of H2 based usages, will hence be driven by carbon neutrality ambitions and not by value creation for the consumers. Furthermore, they are likely to be only relevant in the context of deep decarbonisation objectives. For the project developers, an H2 economy represents very interesting business opportunities, all the more if new large infrastructures are being built in a very short period of time.

We therefore face a paradox:

In the long term, the consensus is that hydrogen will be required to reach a net-zero target. But when explored in details, hydrogen-based solutions seem to have in reality very few advantages for consumers.

Lack of vision for stakeholders to make their investments decisions

The declination of the hydrogen strategy suffers from the lack of long-term vision. This lack of vision impacts may aspects of the hydrogen economy and can be seen in all points of view.

In the system point of view, many important questions remain unanswered. The most important being:

- To what extent do we really need hydrogen?
- What will the hydrogen ecosystems look like and what will be the implications in terms of infrastructure and market?
- How to make sure that the available capital is invested in the most efficient way to reach the given target?

We identified two elements giving some answers to those interrogations.

At first, more and more experts and stakeholders are very aware that the estimation of long-term hydrogen place in the system is a highly speculative exercise. However, we can already assess the "**no regret investments**" on which to focus on right now. This approach enables to have a clearer view on hydrogen prospects by drawing a "minimum market share projection". This approach enables to focus the investments on specific areas and limit the risks of misallocation of capital.

The second trend is to stay **technology neutral** and to focus on the carbon impact. Indeed, with so little certainty about the future of hydrogen, it is wise to keep all the doors open and to make sure only the most efficient solutions to comply with our objective are selected (i.e. reach carbon neutrality at the least cost). The development of mechanisms such as the **EU LTS or carbon contracts for difference** are in that regards key assets. Investment in fundamental research is also important to let ourselves the opportunity to discover new ways to solve this extremely complicated problem, with little cost and potential huge rewards.

In the project developer point of view, the lack of long-term vision manifests itself with the difficulty to construct a viable business model for the following reasons:

- Difficulty to find clients to sell the production to.
- Many uncertainties about the power supply prices for electrolysis.
- Many uncertainties about the selling price of H2.
- The capex of any investment remains very high and the rapidity of the cost reduction is uncertain.

For the consumers this lack of vision concerns:

- The price at which they could get the hydrogen, which is necessary to construct their own business model.

- Very high barriers to entry given the investment costs and only little certainty that hydrogen-based systems are the most suited for their needs.

The 3 major impacts of this lack of long-term vision at all levels that we identified are:

- It postpones the investments.
- Those investments are costlier to take into account a big risk premium.
- The investments remain small, which has itself a negative feedback impact on the learning curve.

Hence, in the long term, the consensus is that hydrogen will be required to reach a net-zero target. But when explored in details, hydrogen-based solutions seem to have in reality very few advantages for consumers.

The role of public support will be essential

These mismatch of interest between a systemic point of view and the consumer point of view, coupled to a lack of long-term vision for the project developers, suggest that **some kind of public support will be needed** for the development of H2 as the benefits are mostly emerging when adopting a system point of view (and not partial ones). The H2 economy is unlikely to develop “by itself”, even if its value for the system is clear.

We identified that hydrogen solutions will require support to be competitive with the carbon intensive solutions. The current momentum and the announced investments clearly indicate a window to act now. The needed support is of different natures:

- Shared long-term vision to reassure the stakeholders on the perennity of their investments and start-up a true hydrogen economy with synergies between actors. Many private actors fear that a shift in regulation could make their businesses collapse.
- Support to help the low carbon solution to be competitive against the carbon intensive solution.

For the first point, many experts call for clear framework as soon as possible for the actors to organise themselves, this should concern: the way carbon content is assessed, the safety rules that will be implement, the usages that will be open to H2 etc. For many, this framework should remain smooth to be adapted to a new system. Questions on unbundling for example should not be a priority as large public networks themselves will not be at the core of H2 development at the beginning.

For the second point, the challenge will be to provide a significant financial support to producers and consumers while avoiding misallocation of capital. This is made even more complicated as, the hydrogen development is at an early stage and a large variety of approaches exist. The current **EU ETS** that could be extended further with a revision on quotas allocation is a very efficient way to have a non-biased, carbon-oriented strategy. Two additional measures can complement this mechanism:

- A **carbon contract for difference (CCFD) mechanism**, that enables industrials to invest in carbon free systems and construct their business model even though they don't have clear vision of the evolution of ETS prices. This mechanism based on auctions is very efficient to make sure that both investments and public support are routed to where it is the most needed in terms of carbon reduction.
- A form of protection to the industrials willing to switch to zero carbon productions, even though the associated cost is much higher. In that concern, many suggest the instauration of a **carbon taxation at the frontiers of EU**. This solution has indeed a strong protection potential but also has many drawbacks like we saw in paragraph 3.1.4.4. It is important that the cure does not become worse than the disease.

When to invest and who will pay for the transition?

We face today a dilemma on hydrogen. If a consensus exists that in the context of a net zero strategy, hydrogen is the only solution that we see today for some application (the sectors with the so called "hard to abate emissions"), hydrogen is not an easy fruit to grasp. Indeed, many of those applications are very expensive compared to other abatement measures and as a result, could be **among the latest abatement solutions to scale up**. However, hydrogen solutions are very capital intensive and require costs reduction to be relevant. In that condition, it is very difficult to postpone the investment to the last minute. Moreover, some of the applications requires the building of heavy hydrogen infrastructures that could take decades to put in place.

The first dilemma is hence on the investment dynamism. Long term investment signals are required to scale up hydrogen investment and prepare the infrastructure. However, the investment objectives remain very blurry as only very little consensus exist on the long-term target. Focusing on the "no regret" investments in hard to abate sector is a way to minimise the risk at reasonable costs.

To summarize the issue, we can use the following analogy: We need to fire the arrow as soon as possible without knowing exactly where the target is nor what the size of the target is.

The second dilemma is "who will pay for the H2 transition"? Will it be the producers? The consumers? The tax payers?

As we saw in the report, it is very complex to rely solely on the **producers** to pay for the transition as the incentives for them are low. Moreover, it could jeopardize the local industries and would cause a lot of competition and trading problems. Finally, the **consumers** at the end of the chain will be in fact the ones to pay for the transition because of higher prices. If the transition cost relies on the consumers (mostly through taxes), it will have a lot of economic impact with a global rise of industrial good prices. Moreover, many consumers cannot handle any price rises: for example, a rise in fertilizer prices would impact the farmers and would induce a rise in basic food prices. Finally, the transition can be borne by the taxpayers through direct subsidies for example. Such mechanism would dilute the price per capita but raise many other issues: lower economic incentive to reduce costs, political acceptance to raise the taxes of everyone, even those who do not feel involved in the energy transition and even if the transition they are paying for is not likely to provide them higher standard of living…

The debate must not be biased. Hydrogen is a powerful asset that we have to try to reach carbon neutrality but by no means it is a magical solution. The transition will imply large investments and probably a lower efficiency. This would lead to a higher cost that need to be paid. Some industrials and investors will enjoy the benefits of the energy transition in general and hydrogen economy in particular. But for the system on the whole, this would be value destructive. This loss of value should not be ignored and must compared to the "cost of inaction".

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