HOW WILL HYDROGEN SHAPE A 2050 DECARBONISED EUROPE?

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EXECUTIVE SUMMARY

Renewable and low-carbon hydrogen as a vector to decarbonise Europe's economy?

- **Hydrogen is regarded by many as a 'Swiss Army knife' in an energy transition scenario where massive electrification comes first**, with the potential to replace hydrocarbons in many applications and sectors where emissions are hard to abate. Wherever clean electrification cannot be fully achieved, clean hydrogen can play a key role for decarbonisation, either as a chemical feedstock or as an energy source.

- **Although many applications could benefit from clean hydrogen, they cannot all be developed simultaneously.** Synergies and incompatibilities between uses must be thoroughly studied in order to find the most efficient hydrogen ecosystem. Strategic choices will not be made based on isolated applications but on comprehensive systems, each of which including a coherent articulation of a certain number of uses. In order to make such choices, policies must be informed with an objective demand side merit order, highlighting the risks and rewards of the different options.

- **Replacing grey hydrogen in existing applications will drive the short-term hydrogen momentum.** The EU hydrogen strategy published in July 2020 emphasises the use of renewable and low-carbon hydrogen to "reduce and replace the use of carbon-intensive hydrogen in refineries, the production of ammonia, and for new forms of methanol production". The real need for clean hydrogen is where no alternative as chemical feedstock is possible (crude oil refining, ammonia, and methanol).

- **Synthetic fuels (or e-fuels) derived from clean hydrogen will likely replace fossil fuels in the long term and limit the need for the electrification of certain uses on the demand side.** Although fuel cell vehicles have limited potential in comparison to battery-based equivalents, hydrogen – in the form of e-fuels - could offer a sustainable alternative to conventional fossil fuels in maritime transport and long-haul aviation, as well as for industrial heat demand. However, the electrification of demand side uses must not be neglected, at the risk of a fossil fuel lock-in dependency.

- **In the medium-term, clean hydrogen could be used as a source of flexibility for the European power system.** According to binding targets set out by the European Union, the share of renewable energy must reach at least 40% by 2030. The high penetration of renewable and intermittent energy generation on the system will require increasing and new sources of flexibility. In this context, clean hydrogen is expected to play a crucial role in helping to the balance of the power system by providing seasonal power storage and dispatchable generation. Despite its low energy efficiency, hydrogen could provide a relevant solution to complete flexibility needs with its long-term storage potential.

How should European energy infrastructures evolve to efficiently integrate hydrogen uses?

- **Transport and storage markets are still underdeveloped since today, hydrogen economy is mostly connected to captive markets** where the molecule is produced and consumed on site and is valued within regional ecosystems (mainly for ammonia production and petroleum refining). However, the emergence of new hydrogen applications in multiple energy and industrial sectors will require the development of a large-scale transport and storage system.

- **Geographic separation of production and end-use will be necessary** when low-cost renewable electricity is unavailable at the consumption site. It will be important to consider the specificities of the European energy system in selecting the regions where clean hydrogen can be produced at a low cost (e.g. Iberian Peninsula) and transported to regions where clean hydrogen is highly valued.

- **The most appropriate and cost-effective way of transporting hydrogen depends on two main parameters: distance and volume of hydrogen transported.** Three scales could be defined for hydrogen transportation: local, regional, and international.
  An analysis of transportation costs enables the **calculation of ''all-in delivered cost of hydrogen" for several configurations by 2050**. The following conclusions can be drawn: (i) local hydrogen production and delivery is often competitive, but depends on the availability of local, low-carbon and low-cost renewable electricity; (ii) ammonia shipping seems to be an interesting alternative for intercontinental transport, especially when ammonia is the final use (e.g. in fertilizer industry); (iii) hydrogen transport by pipeline remains the most economical solution, especially for international-scale transport when H_2 molecule is the final use.

- **Another energy infrastructure development model** is being considered today at the European scale: the **transport of renewable and low-carbon electricity directly from favourable production locations to hydrogen consumption areas**. Therefore, there is a need to develop and reinforce the European electricity grid - especially the interconnection capacity between countries - to transmit low-cost and low-carbon electricity to hydrogen consumers.

- **The low density of the hydrogen molecule makes its storage challenging in comparison with fossil-based energy sources.** So far, hydrogen have mainly had captive uses, requiring extremely limited storage capacities. However, the emergence of a global hydrogen economy **will need a very significant storage capacity**. Being able to store the molecule in large quantities will be one of the most important challenges for the future of the clean hydrogen industry.

- **Large-scale geological storage will be the cornerstone** for the development of the clean hydrogen economy. Three types of geological storage can be distinguished: depleted oil & gas fields, rock caverns and salt caverns. **Salt caverns are considered as the most relevant large-scale geological storage for hydrogen**, characterised by their low-cost storage (around $0.11/kg) and their capacity to deliver large volumes of hydrogen within a short time scale (approximately 1 month).

- **The social acceptability and security challenges related to infrastructures development** are also important to consider since hydrogen has always been an industrial molecule that is very rarely used in urban environments.

How is hydrogen expected to be an accepted and central part of a future clean energy system at a European level?

- The study results highlight the need for Europe to **transition from a centralised and largely decoupled energy system – that relies on imported fossil fuels - to an integrated one**, where the plurality of energy sectors (power, heat and transport) are coupled on the basis of direct and indirect electrification. **Sector coupling is thus a key enabler to reduce greenhouse gas (GHG) emissions in the European energy sector.** This depends on the deployment of different power-to-X technologies (power-to-gas, power-to-fuel, power-to-heat, etc.): **the greater the number of power-to-X projects the higher the degree of sector coupling**.

- **Hydrogen is part of a complex and integrated energy system and cannot be treated separately.** In particular, renewable energy-based hydrogen emerges as one of the most important energy carriers of the energy transition, mainly for the production of synthetic fuels (gas and liquid fuels). While using direct electricity is an efficient solution in a number of cases, **it is difficult to completely replace fuel use in certain applications** (high temperature industrial heating, maritime transport, aviation, chemical feedstock).

- **Water electrolysis is likely to remain the main process for hydrogen production between 2030 and 2050.** The increase in hydrogen production through electrolysis will be enabled by a massive deployment of low-cost solar and wind power as prime energy carriers. This sets the direction towards a truly decentralised, flexible, and demand-driven energy system.

- **Low-carbon hydrogen production based on Steam Methane Reforming (SMR) and Carbon Capture Transportation and Storage (CCTS) could find a niche in the hydrogen market**, so long as natural gas cost is low and hydrogen storage cost remains significantly higher than traditional methane storage.
Its **main role in the 2050 energy system is to provide base supply of hydrogen and increase the flexibility of electrolysers**. SMR + CCTS is expected to cover about 25% of total hydrogen demand, the rest being covered by renewable hydrogen.

- Electrolysers' installed capacities will be distributed across Europe, with the **higher capacities operating in Iberia and Turkey**: electricity supply being the main expenditure, renewable hydrogen will be developped where renewable electricity is the cheapest. Over 1300 GW of electrolyser capacity are expected to be installed by 2050.

- To feed the electrolysers' capacity, low-cost and low-carbon renewable electricity is needed across the several European regions. The analysis showed that by 2050, the average Levelised Cost of Energy (LCOE) is around **€38/MWh**. However, there are **significant regional differences in LCOEs**, with southern countries showing lower electricity production costs due to a higher share of utility-scale solar systems. For example, the **LCOE for producing renewable electricity in Iberia and Turkey falls below €20/MWh**, which also explains the higher share of electrolyser capacity in these regions.

What are the policy recommendations to boost the development of a European hydrogen economy?

- The European vision should be based on a **long-term vision** with **short-term decisions** (e.g. by accelerating the introduction of new hydrogen funding schemes). Choices regarding investments need to be made in the short-term considering the time required (between 5 and 10 years) to deploy new hydrogen infrastructures. **Current initiatives and projects are promising, but not enough to trigger the transformation** of the European energy system towards a clean hydrogen economy.

- **The current European regulatory framework is still lacking tools to allow a true hydrogen scale-up**, and more generally to support decarbonisation solutions in their competition with existing carbon-intensive processes. **Four development axes** appear to be critical in the process of enabling a net-zero emission energy system based on a sustainable hydrogen economy: (i) the development of incentives for carbon abatement technologies and uses; (ii) innovation and research on the supply side to target viable business models; (iii) ensuring the bankability of investments in low-carbon solutions; and (iv) the support for an efficient and consistent energy system integration between supply and demand.

- **Granting access to low-cost renewable electricity is a key enabler for clean hydrogen development** since renewable hydrogen projects expenditures mainly consist in electricity supply cost, which represents 60-70% of the total costs. Contrary to what might be assumed, technological advances and CAPEX reduction alone will not solve the economic issue of the emerging industry.

- **A global coordination between all the European stakeholders is needed** to set the infrastructure development strategy and finetune the economic, social and political stakes of each approach. Coordinating countries' ambitions should be supported by appropriate funding schemes (such as the IPCEI for example) that foster national cooperation and help aligning the different strategies and initiatives.

- Pending the pipelines' conversion, **blending hydrogen with natural gas** should be accelerated in the coming years to meet a potential short-term increase of hydrogen demand (especially for industrial and domestic heating).

- **Finally, hydrogen standards and certifications are needed to structure the market.** Such standards should cover (i) classification terminology for all clean hydrogen production (renewable hydrogen, low-carbon hydrogen, ...), (ii) safety issues in regards of hydrogen and ammonia handling, and (iii) hydrogen purity levels. The development of a European certification system (based on renewable and low-carbon Guarantees of Origins) as well as an appropriate regulatory framework will boost private investments and support the development of a clean hydrogen economy.

Introduction

There have been periodic waves of enthusiasm for the potential of hydrogen as a source of energy since the middle of the 20th century. However, none of the previous cycles of enthusiasm has succeeded to sustainably develop a global hydrogen economy, in a context characterised by relatively low oil and gas prices. Hydrogen remained a **feedstock for several industrial processes** (petrochemical refining, ammonia, steel manufacturing, etc.), with a very limited use as an energy carrier. Globally, about **70 Mt of hydrogen is consumed each year**[1] in its pure form. The molecule production process is almost entirely fuelled from fossil-based energy sources (grey hydrogen produced via Steam Methane Reforming and Coal gasification) and is therefore responsible of **830 million tonnes of carbon dioxide (CO_2) per year**[1], the equivalent of the CO_{2eq} emissions of France and Spain combined.

However, only very recently has hydrogen gained popularity in political and scientific discussions as a **promising energy carrier** contributing to tackle climate change. Compared to the existing fossil-based hydrogen market, the growing interest in clean hydrogen is based on the fact that it can be produced and used without direct emission of greenhouse gases (GHG) or air pollutants. It can thus contribute to a resilient and sustainable energy future by **decarbonising existing industrial applications** and developing a **wide range of new applications** where emissions are **hard to abate** (transport, heating, steel production, etc.). For these new markets, the molecule can be used in its pure form or transformed into **e-fuels** (synthetic methane and liquid fuels, ammonia, and methanol).

This time, the unprecedented momentum for clean hydrogen is real, with a **historic political commitment** by many countries: Australia, Japan, Chili, several European

Source: [1] IEA, 2019

countries, China, Morocco, New Zealand, and more with clear ambitions and roadmaps for clean hydrogen development. Currently, there are **more than 20 hydrogen strategies and roadmaps unveiled** around the world[1]. While the context, challenges and enabling factors may differ from a national strategy to another, there is a clear global consensus on the fact that clean hydrogen is not only a bridging technology, but also a crucial and essential part of a carbon-neutral global economy.

However, the path for hydrogen to reach its full potential is still long, both on supply and demand sides. On the **supply side**, it is critical to ensure that the produced molecule has the lowest possible carbon footprint. **Two types of clean hydrogen** can be distinguished: **renewable hydrogen** (so-called green hydrogen) and **low-carbon hydrogen** (so-called blue hydrogen). Renewable hydrogen is produced by water electrolysis using renewable electricity (solar PV, wind, etc.), and its carbon footprint depends only on the GHG emissions of the electricity source (emission reported in the scope 2 of the GHG Protocol, using a Life Cycle Analysis approach). Low-carbon hydrogen on the other hand is produced via conventional processes, such as Steam Methane Reforming (SMR), combined with Carbon Capture, Utilization and Storage (CCUS) technologies to reduce its CO_2 direct emissions. Low-carbon H_2 production process is not carbon free since about 10% of CO_2 emissions are not captured with CCUS technologies operating today[2] (emission reported in the scope 1 of the GHG Protocol). Is also considered "low-carbon" any hydrogen produced using low-carbon electricity, the carbon footprint of which is below a certain threshold (still to be defined at a European level). Today, there are **no established standards and classification terminology** for all clean hydrogen production, which negatively impacts the development of sustainable hydrogen projects.

On the **demand side**, a number of transformations are needed to switch from a deeply fossil economy to a decarbonised hydrogen one.

The **private sector must be supported** to integrate hydrogen in their processes: the current regulatory framework still lacks specific tools to allow a proper hydrogen scale-up to compete with existing carbon-intensive processes.

Although there is global interest in the potential of hydrogen, it is important to note that it is not a ''silver bullet" in tackling climate change, but a **key part of a complex carbon-free energy system** to be developed, and it must be treated as such.

The main challenge in Europe will be the development of a **consistent hydrogen infrastructure**. Bolstering supply and demand will not be sufficient to durably integrate hydrogen production and usage if their development is disconnected. Several hydrogen clusters have been unveiled over the past months, enabling the emergence of local hydrogen economies. The potential of such clusters is yet limited, and Europe has to develop a global infrastructure in order to **deploy hydrogen at a larger scale**. Such infrastructure will only be achieved through **collaboration** between the several European countries.

This study aims to analyse the potential of hydrogen for **energy and industry sectors' decarbonisation by 2050** (part 1), the inherent hydrogen infrastructure that needs to be developed (part II), the place hydrogen is expected to fill on a European scale by 2050 (part III) and the policies that must be enforced in order to make it happen (part IV).

The analyses rely on a **state-of-art review, information gathered through interviews** and on a **holistic energy system modelling** that integrates a wide range of existing and future energy technologies with the most up-to-date knowledge and data. Although the results for 2050 are up to debate, the purpose of this study is to understand the major trends that the development of renewable and low-carbon hydrogen will follow.

Sources: [1] Yélé Consulting, 2020; [2] Energy Cities, 2020

I. The potential of hydrogen to decarbonise the European economy

Massive clean electrification seems to be the most efficient way to meet the European carbon-free target by 2050. With decreasing all-in generation cost and clear efficiency gains, clean electrification is expected to lower the total energy system costs while granting environmental benefits.

However, direct electrification cannot be achieved in all areas of economic activity, as it appears to remain impossible or highly uneconomic in some sectors. In many of these sectors, renewable and low-carbon hydrogen can play a key role in economy decarbonisation: despite its low cycle efficiency, **hydrogen is considered as the 'Swiss Army knife' of the green energy future** with the potential to replace hydrocarbons in many applications and sectors where emissions are hard-to-abate. Hard-to-abate emissions include shipping, iron and steel production, high-temperature industrial heat, long-distance and long-haul road transport.

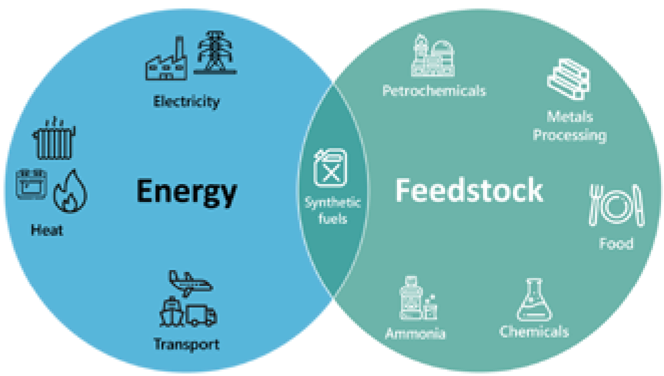

Fig. 1. Hydrogen applications as energy carrier and feedstock
(Source: Yélé Consulting)

The role of hydrogen differs depending on the sector it is used in:

- **As a chemical agent or feedstock**, hydrogen is the base material for several industries (ammonia, methanol, etc.) and presents interesting chemical properties that could play a role in plastics and steel processes.
- **As an energy source**, hydrogen (as well as its derived products) presents a high energy density per mass that offers potential opportunities to decarbonize some industrial and long-distance transport applications. It provides an additional flexibility for the power system and can bring an affordable solution to seasonal storage.

Considering all of its current and potential applications, the global hydrogen market could skyrocket from today's 80 Mt per annum to reach **1 400 Mt[1] by 2050**, with hydrogen (and its derivatives) accounting for approximately 20% of global final energy demand.

In theory, hydrogen could be used for industrial uses, transport, heating, and power. However, its relevance is arguable for some of these applications. To understand the **appropriateness of hydrogen for each sector**, this part of the study includes a **demand side merit order** highlighting the most relevant applications it can be used for. This provides an indication of the applications that must be prioritised for the use of hydrogen. This merit order is based on the environmental and energy performance of each application (GHG emission reduction potential) as well as its deployment potential (technical and economic feasibility, availability or not of alternative low-carbon solutions, ...).
Although the **overall positioning can be questioned**, the main purpose of such merit order is to help to identify key priorities and seize the potential of hydrogen for each sector.

The applications in Fig. 2. can be grouped into **3 main categories:**

- **Industrial** hydrogen applications that present a **strong decarbonisation potential**
- **E-fuels** (energy vectors derived from hydrogen) for heat and transport applications
- **Fuel cell uses** (mainly for road transport)

The chart (fig. 2) indicates the potential for each application taken apart and **does not consider the possible synergies between hydrogen uses.** For example, H2VC trucks could be developed if coupled with the emergence of industrial hydrogen valleys (see paragraph "The high potential of Hydrogen Valleys" below).

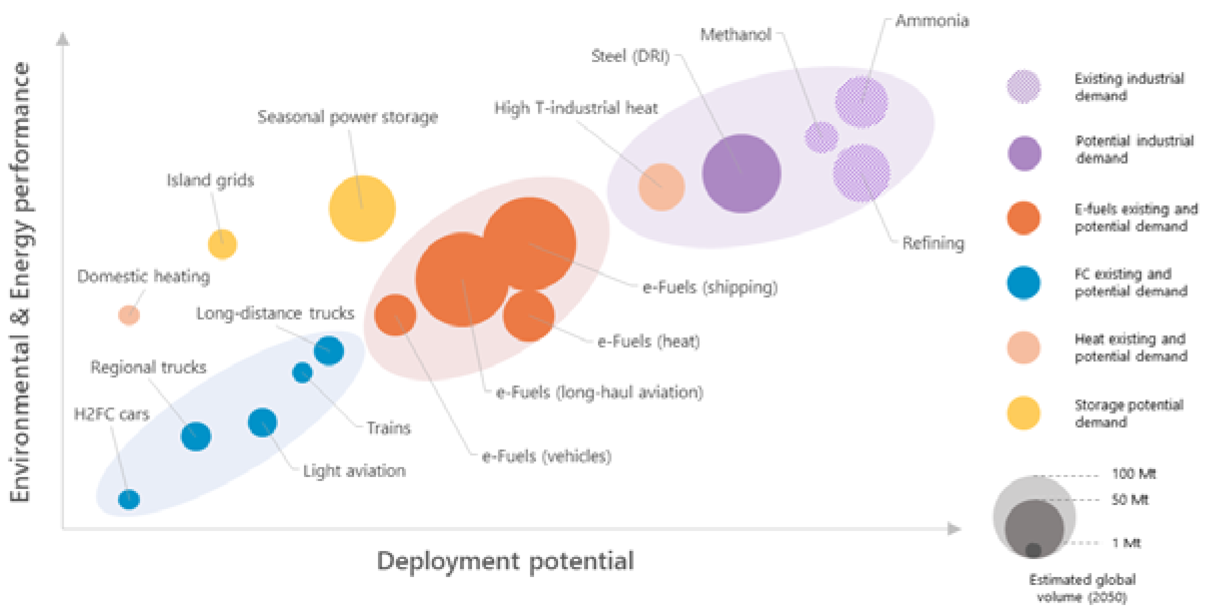

Fig. 2. Demand side merit order (Source: Yélé Consulting)

Source: [1] LUT University, 2021

REPLACING GREY HYDROGEN AS A PRIORITY

The EU hydrogen strategy published in July 2020 emphasises the use of renewable and low-carbon hydrogen to "**reduce and replace the use of carbon-intensive hydrogen in refineries, the production of ammonia, and for new forms of methanol production**"[1]. It appears quite clearly that industry applications will drive the hydrogen momentum: **the real need for clean hydrogen is where no alternative as a chemical feedstock is possible** (crude oil refining, ammonia and methanol).

Most of hydrogen produced today is consumed as chemical feedstock, 95%[2] of which coming from hydrocarbons (so-called grey hydrogen). Replacing this carbon-intensive hydrogen with a clean one would reduce EU's CO_2 emissions by 2.2%[3], in sectors where electricity cannot act as a substitute: focusing first on the existing markets is the easiest way to promote hydrogen as a low-carbon economy enabler.

The use of clean hydrogen in new industrial processes

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The main use potencial of hydrogen as a chemical agent in industry is for steelmaking. The steel industry is among the largest carbon emitters (8%[4] of EU emissions in 2020) and is thus seeking ways to decarbonise its processes.
Clean hydrogen is currently being tested as a replacement for coke in the steel industry through *Hydrogen Direct Reduced Iron* (H-DIR) or H_2 Plasma Smelting Reduction. Although promising, both of these processes remain experimental and are only expected to be developed by 2030-2040. In the meantime, similar technologies are being developed **using natural gas as a key resource first**. In addition, several pilot projects are exploring the potential to co-feed hydrogen in existing blast furnaces and provide an incremental GHG performance improvement during the transition period.

In their 2019 cost of fossil-free steel analysis, BloombergNEF concluded that competing with current steel production would require a **€0.6 – 2.5/kgH_2 hydrogen price**. Although the upper limit seems easily manageable in a near future, dropping below €1/kgH_2 seems more challenging, depending mainly on RE cost reductions by 2050.

Other industries, such as **cement and paper industries**, show a minor potential for hydrogen usage, with an estimated consumption of less than 2 Mt in 2050[5]. Electrification and Carbon Capture and Storage (CCS) will be stronger decarbonisation drivers in these sectors than hydrogen.

Plastics and other chemical production where hydrogen could be an input are also targeted for new production processes (Methanol-to-Olefin or Methanol-to-Aromatics for instance), but they require sustainable CO_2 sources first. These applications could also benefit from more effective decarbonisation options.

Sources: [1] European Commission, 2020; [2] IEA, 2019; [3] IEA, 2019; [4] IEA, 2021; [5] Deloitte, Hydrogen4EU, 2021

E-FUELS: THE FUTURE OF CLEAN HYDROGEN DEMAND

Although hydrogen can be used as an energy carrier in its pure form via fuel cells (FC), its **derived products appear to be far more promising**. E-fuels (electricity-based synthetic fuels) are **hydrocarbon fuels synthesised from clean hydrogen and captured CO_2**. Their characteristics make them environmentally interesting substitutes from a sustainability point of view, as they have a high energy density, storability, transportability and combustibility. The use of **e-fuels is a promising alternative to using fossil fuels and allows for the integration of renewable energy without going through the expensive transformations that direct electrification would require**. In addition, due to safety and security reasons, synthetic fuels remain easier to handle than hydrogen.
The production processes of e-fuels are depicted in figure 3.

E-fuels could be promising in sectors and applications where direct electrification is a challenge. **Three applications are especially targeted**: shipping, long-distance aviation, and high temperature heating processes.

In the maritime sector, aiming for zero-carbon shipping means using zero-carbon fuels. Biogas is an effective fuel, but its production potential is limited. Crop-based biodiesel, once supported by the Renewable Energy Directive (RED), is gradually being phased[1] out from EU support schemes because of its negative environmental impact. **Hydrogen-based e-fuels seem to offer the only valid alternative** for zero-carbon shipping. It is already being studied by maritime engine manufacturers such as Maersk or Wärtsilä.

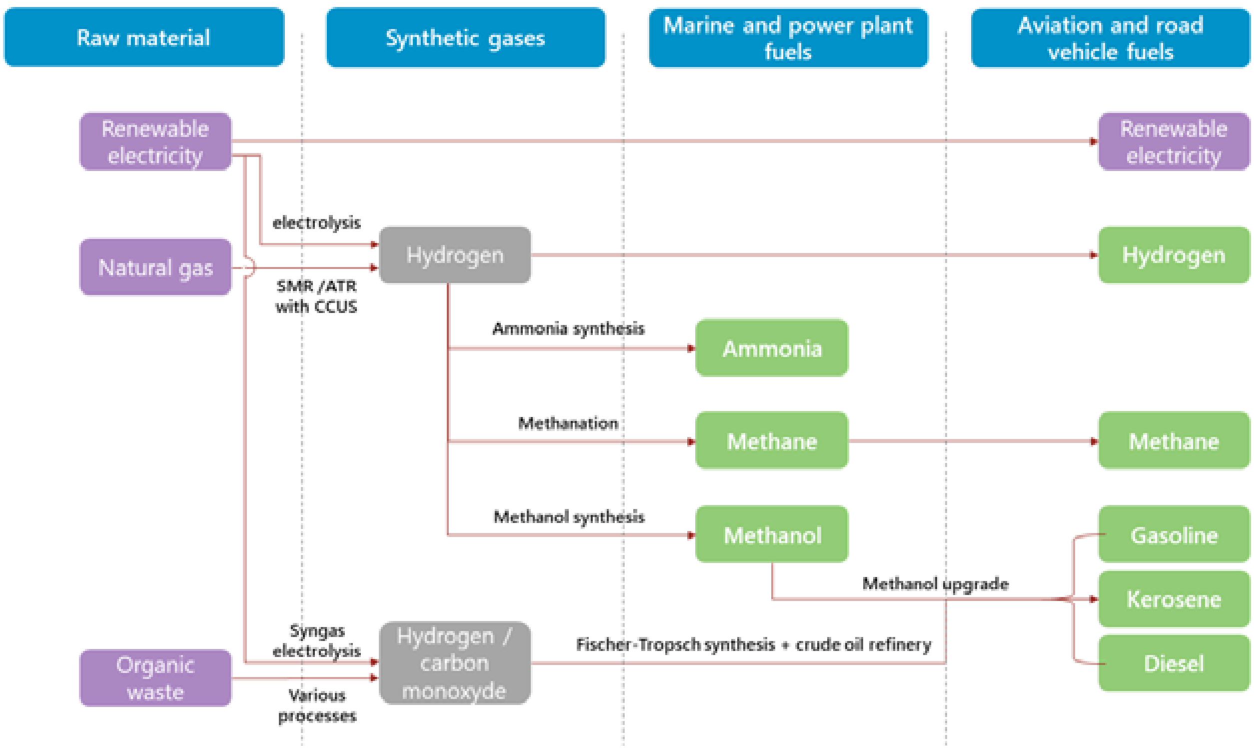

Fig. 3. E-fuels production processes
(Source: Yélé Consulting)

Source: [1] *European Commission, 2020*

In May 2021, a consortium of several "green" maritime organisations delivered a letter to the European Commission, stating that EU should promote the use of green synthetic fuels as part of its upcoming maritime and aviation fuel laws (FuelEU Maritime and ReFuelEU initiatives)[1].

In the case of long-haul aviation, although experts agree that the development of hydrogen-powered planes is too challenging today, **synthetic "power-to-liquid" jet fuel might be required to meet the needs of the global aviation industry**. A recent report from ATAG (Air Transport Action Group)[2] suggests that synthetic fuels will be developed significantly in the long term, as part of the various Sustainable Aviation Fuels (SAF) routes.

However, the potential for hydrogen use in the heat sector is more nuanced. Electrification provides an affordable solution to decarbonise the heat sector. Despite the technological uncertainties around the potential for hydrogen to be used in heating systems, some observations can be drawn:

- Using e-fuels for low-temperature heat demand (<400°C) would require 10-14 times more electricity than heat pumps[3], making **e-fuels most likely unviable for water and space heating**.
- In terms of electricity-to-useful-energy efficiency, e-fuel powered boilers would require twice as much electricity than electric furnaces/boilers. Considering the expected low-cost of renewable electricity, this factor does not justify the development of an expensive electric infrastructure. In addition, electricity will not grant the same security of supply than the conventional processes do. **E-fuels are thus considered relevant for high-temperature heat applications.**

While **e-fuels have both the environmental and economic potential to replace fossil fuels in the long term**, electric transformations must not be neglected: should e-fuels fall short of their expected potential, the European energy system would otherwise remain locked in a fossil fuel dependency.
The risks associated with the development of hydrogen and synthetic fuels once again highlight the fact that a **sustainable carbon free economy can only be reached through a combination of complementary solutions mitigating the risks**.

Reaching an economic viability regarding conventional fuels

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Although e-fuels appear relevant for the replacement of fossil fuels, their economic viability has yet to be proved. According to a recent study[3], e-fuel production costs are estimated at €194-226 / MWh. In order to **compete with fossil fuels**, carbon price must rise to €800/tCO_2 for e-gasoline and €1 200/tCO_2 for e-methane (carbon current price being around €50/tCO_2). While these projected costs are unrealistic, the cost of hydrogen and e-fuels are expected to drop drastically: by 2050, the fuel switching CO_2 prices are estimated at €20/tCO_2 for e-gasoline and €270/tCO_2 for e-methane. Such prices are completely within the range of prices of the EU ETS, **making e-fuels economically viable in the long term**.

Sources: [1] European Commission, 2020; [2] ATAG, 2020; [3] Nature, 2021

LIMITED OPPORTUNITIES FOR HYDROGEN AS A DIRECT ENERGY CARRIER FOR TRANSPORTATION

A dead end for light road transport

Even if it has been announced as the "future of mobility" for the past 20 years (George W. Bush once predicted that fuel cell cars would be competitive with internal combustion engines by 2010)[1], evidence shows otherwise. Most carmakers have delayed – if not abandoned – their H_2FC programs because of the **lack of market opportunities[2]**.

Leaving aside the economic challenge, **the main obstacle for the development of fuel cell electric vehicles (FCEV) is their low energy efficiency compared to battery electric vehicles (BEV)**. Many factors impact their efficiency as a solution for mobility: the conversion rate of electrolysis, losses in compression, storage as well as transport.
As for the vehicle autonomy (core argument for the development of FCEV), the lack of autonomy of BEV is expected to be fully compensated by the density of the upcoming EV charging infrastructure as detailed in the "Fit for 55" policy package[3]. Same logic is all the more true for local public transportation, delivery vans, industrial and service vehicles, with predictable journeys that can be easily made using BEV.
Additionally, the FCEV will always be **more technically complex compared to BEV**, as there is an additional step of energy conversion from hydrogen to electricity and consequently a need for additional equipment. **The argument defending that FCEV require less battery storage capacity compared to BEV becomes less relevant** as the cost of battery storage has declined in the last decade, and superchargers have improved substantially in recent years[2].

Furthermore, the automobile industry has already started its transformation towards electric vehicles, and it is unlikely to shift towards developing an automobile hydrogen industry. The same is true for the road infrastructure - it is unlikely that there will be a twofold transformation towards electric and hydrogen-powered mobility simultaneously. **Direct electrification will remain a more sustainable option in comparison with FCEV in this market segment.**

A narrow opportunity for heavy road transportation and train

When it comes to long distance transportation, hydrogen may have a role to play, but **its relative advantages versus other options for decarbonisation remain unclear**.
The dramatic fall in the price of lithium-ion batteries and steady improvements in battery energy density and charging times have widened the distance and size ranges[2] across which BEVs can compete with FCEVs. This has been largely aided by businesses enabling overnight depot charging. Biogas-powered trucks also seem to provide a viable option for such journeys, limiting the need to develop hydrogen for this type of transportation.
Hydrogen could also find a place in specific use cases of rail transport. While railway electrification remain the most interesting option for busy lines, H2-powered trains (e.g. Coradia iLint, Alstom) represent a good opportunity to decarbonise little-used regional railway lines, with relatively low traffic (passage frequency >1h)[4]. Hydrogen is especially relevant for the lines with the lowest electrifications rates, offering a complementary, economically viable and easy to implement solution.
Furthermore, such development could create synergies with local hydrogen ecosystems and boost the emergence of hydrogen hubs (see paragraph "The high potential of Hydrogen Valleys" below).

Sources: [1] White house archives, 2003; [2] Liebreich, 2020; [3] European Commission, 2021; [4] ADEME, 2020

SITUATIONAL APPLICATION – HYDROGEN AS A SOURCE OF FLEXIBILITY FOR THE POWER SYSTEM

As a **dispatchable energy source** within a power system massively based on intermittent renewable electricity (RE), hydrogen is expected to play a crucial role in balancing the power system by providing **seasonal power storage**.

The most optimistic RE-based long-term scenarios consider that it would be possible for the power system to cover 80-90% of load demand peaks by 2050, using an interconnected power grid with conventional flexibility (storage, demand response, curtailment)[3]. The remaining 10-20%, however, will be more challenging to deliver as conventional means of flexibility will not be able to grant a sufficient assurance for power supply (in the case of exceptional cold waves for instance).
Due to the intermittent nature of such a power system, **the additional dispatchable generation sources will have to operate on a low load factor**. Conventional power plants are not appropriate and will not be able to meet this need.

A hydrogen carrier, however, with its massive storage potential (as described in the next section), is a relevant option to satisfy the remaining demand of the power system. **Despite its low energy efficiency (25-35%)[1], the Power-to-Gas-to-Power (P2G2P) process is worth considering.** Electrolysers could be combined with appropriate heat recuperation technologies, thus improving their overall efficiency and bankability.

The need for flexibility from hydrogen to balance the system is a medium-term concern. The French TSO RTE stated that the French power system would not need hydrogen as an additional flexibility source before 2040[2]. This may be specific to the French electricity system as there is a limited need for additional flexibility on the grid. In all cases, the need for flexibility from hydrogen will not appear in Europe in the next decade.

Sources: [1] Energy Transitions Commission, 2021; [2] RTE, 2020; [3] Liebreich, 2020

Hydrogen as a relevant solution for non-interconnected power systems

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Due to their specific power needs, non-interconnected zones (e.g. islands) have been targeted through **public funding as experimental playgrounds for Minigrids and Microgrids**. Based on RE sources (wind, solar, hydro, biofuel, etc.), these systems generally need backup generators and storage to address energy intermittency. While conventional fuels such as diesel remain the most adopted solution to enhance the reliability of RE mini and micrograds, other options are being considered to address the impact on GHG emissions of these solutions. **Hydrogen is one of these solutions as a provider of storage and flexibility capacities** while shifting away **from the use of fossil fuels**.

Several initiatives, such as the **Mafate microgrid project launched in 2017 by EDF and Powidian**[1] on La Réunion Island, have been conducted so far and they provide optimistic feedback on the potential of hydrogen for such isolated locations.

Nevertheless, most non-interconnected zones still have important changes to make before hydrogen becomes a relevant part of their mix: the effective development of the molecule in these environments is likely to be **a medium-term concern**.

THE HIGH POTENTIAL OF HYDROGEN VALLEYS

To enable the emergence of a **locally integrated hydrogen ecosystem, enhance the integration of local RE in an efficient energy system, and mitigate the financial risks of isolated development**, hydrogen actors have started gathering around hydrogen clusters, or "Hydrogen Valleys" as they are referred to by the Fuel Cells Hydrogen Joint Undertaking (FCH JU)[2]. Such clusters gather several local actors (industrials, RE producer, gas DSO and TSO, institutional actors, etc.) that **cover most of the hydrogen value chain** (from production, storage, transport and final use).

Hydrogen Valleys are expected to grow in number and in complexity by 2030. What started off as a public-driven initiative is slowly being taken over by the private sector, since such projects are considered as strategic for the future of the energy system.

Being part of hydrogen cluster is reassuring for both supply and demand sides stakeholders, since it **supports the development of synergies between different end uses** to achieve large economies of scale. More specifically, by regrouping and sharing infrastructure assets, hydrogen clusters **bolster the development of some end uses that would not find an economical balance otherwise**. For example, despite its uneconomic business model, hydrogen local mobility could be considered in such industrial clusters thanks to **synergies with other industrial processes that bear most of the costs**. This will also help secure the **appropriate funding schemes for hydrogen clusters**, which is necessary to boost their development by 2030.

Although the specificities of hydrogen clusters will depend on the local characteristics and requirements, a few trends have emerged. **Three typical setups are expected to be developed in the next few years, as described below.**

Sources: [1] CRE, 2020; [2] FCH JU, 2021

	PORTS	MOBILITY HUBS	INDUSTRIAL END-USERS
	Ports are strategic import/export nodes that benefit greatly from e-fuels as a mean of maritime decarbonisation. They are often located near heavy industrial sites, thus increasing the potential for clean hydrogen demand.	Mobility hubs can provide hydrogen and e-fuels where it is most needed, in populated areas such as cities, airports or international (non maritime) hubs.	Existing applications (refineries, ammonia, methanol) and steelmaking offer a sufficient stand-alone hydrogen demand. However, clusters offer risk-mitigating possibilities as well as reduced investments.
Range	large-scale international projects	medium-scale projects	medium-scale projects
Size	100 – 1 000 tH_2/day	10 – 500 tH_2/day	100 – 300 tH_2/day
Example of International projects	**H2Gate : Port of Amsterdam** – 1 Mt/year, interaction with local industries (Nouryon, Tata Steel) **North Sea Port** – 500MW, near end users include ammonia and steel plants	**H2 Hub Airport (France)** – 11 projects selected to transform Paris airports into hydrogen hubs, starting in 2023 **Hydrogen cities of South Korea** – 4 cities that will use hydrogen as a fuel for urban functions such as heating, electricity and transportation by 2022.	**Puertollano (Spain) ammonia plant** – renewable hydrogen used to feed part of the ammonia production **HYBRIT initiative (Sweden)** – SSAB, LKAB, Vattenfall exploring hydrogen application in steelmaking (DIR). Pilot phase expected to last until 2024; €44M funded from the Swedish Energy Agency

Fig. 4. Typical hydrogen valley setups
(Source: Yélé Consulting, adapted from Energy Transitions Commission, 2021)

However, **clusters alone will not allow hydrogen to meet the ambition of becoming an integrated energy carrier in a fully decarbonised economy by 2050.**

A global European infrastructure for hydrogen transportation and storage is required to interconnect the several clusters and build a global market for the molecule.

II. A needed development of the European H_2 transport and storage infrastructures

Today, the **hydrogen economy is mostly connected to captive markets**, where the molecule is produced and consumed on site within territorial ecosystems (mainly for ammonia production and petroleum refining). Therefore, **transport and storage markets are still under-developed**. However, eventually, the development of new hydrogen applications in multiple energy and industrial sectors will **require a large-scale transport and storage system**. In particular, geographic separation between hydrogen production and its end-use will be necessary when the appropriate favourable resources (low-cost renewable electricity, for example) are not available on the consumption site.

Taking into account the local specificities of the European energy system, it may therefore be interesting to **produce hydrogen in certain locations where energy costs are low** (e.g. Iberian Peninsula) and **transport it to regions where hydrogen is highly valued**.
However, **developing transport and storage involves additional costs, which are higher when hydrogen is used within smaller scale distributed systems**. Therefore, the economic viability of a large-scale hydrogen transportation and storage system will be determined by the cost differential compared to the development of local production.

Based on the information gathered through the interviews as well as the state-of-the-art review, this part provides a specific technical and economic analysis of:

- Hydrogen transport scales and options.
- Large-scale geological storage.
- An alternative to the transport of H_2 molecules, using renewable and low-carbon electricity transport.
- The need to coordinate the efforts at a European scale.
- Some examples of hydrogen projects and initiatives at European level.

TRANSPORTATION SCALES AND OPTIONS

The form in which hydrogen is transported is a key element when considering **how supply can meet demand**. It can be transported as compressed gas (pressures up to 1000 bar) or in liquid form (at -253 °C)[1]. However, its low density makes it considerably expensive to transport, especially via road and maritime travel.
Alternatively, the molecule can also be **moved via hydrogen carriers, namely ammonia and Liquid Organic Hydrogen Carriers (LOHC)**. Although ammonia is a mature and industrialised solution, LOHC is still at a lower Technology Readiness Level (TRL) today and needs specific developments before being considered a viable solution for transportation projects.

Several scales could be defined for hydrogen transportation:

- **Local-scale hydrogen transportation:** for low volumes and short distances, hydrogen is transported via compressed hydrogen tube trailers on trucks. This is particularly the case today for small industrial actors as well as for hydrogen refueling stations. For larger volumes exceeding 10 tons per day, pipeline technology becomes the most appropriate transportation option from an economic standpoint (e.g. Port Jerome industrial hub in Normandy, where hydrogen is locally transported via pipeline to a nearby refinery).
- **Regional-scale hydrogen transportation:** for longer distances (between about 100 km and 1000 km) and small volumes, liquid hydrogen road transport remains the most cost-effective option, although costs rise depending on the covered distance. However, pipelines are likely to be the lowest-cost means for transporting larger volumes. There are today about 4,500 km of operating hydrogen pipelines globally[2], which is considered insufficient to support a wholescale adoption of the molecule.
- **International-scale hydrogen transportation:** the development of a global hydrogen economy will need ships to transport hydrogen between the different continents, from countries disposing of low-cost renewable electricity to industrial countries needing low-cost and low-carbon hydrogen to decarbonise their industries. Shipping hydrogen as ammonia (Example: the Ammonia Wrap[3], an initiative for an ammonia-powered shipping network in northern Europe) is likely to be a promising solution for long distance shipping, especially when ammonia is the end-use (thus avoiding the costs of reconversion to hydrogen at destination).

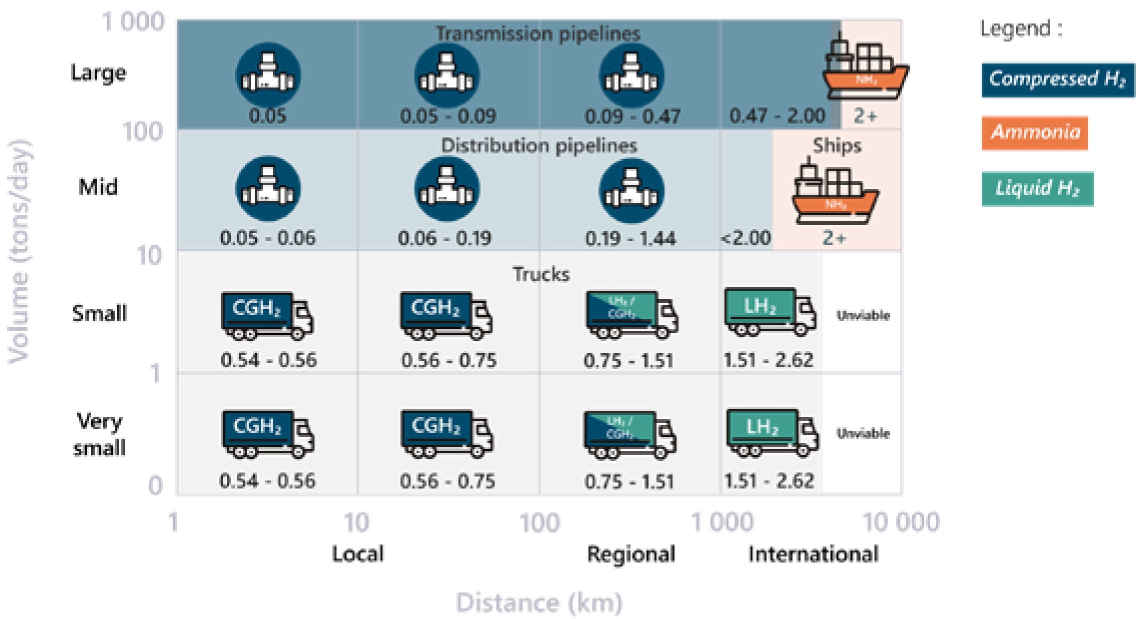

Fig. 5. Hydrogen transportation costs (\$/kgH_2) based on volume and distance
(Source: Yélé Consulting, adapted from BloombergNEF, 2019 and Energy Transitions Commission, 2021)

Sources: [1] Air Liquide, 2021; [2] Energy Transition Commission, 2021; [3] Ammonia Energy, 2021

The most appropriate and cost-effective mode for hydrogen transportation depends on **two main parameters: distance and volume involved**. Figure 5 details the most economical solution in each specific case.

The analysis of transportation costs enables the calculation of the ''all-in delivered cost of hydrogen" (including production, transport and storage) for several configurations by 2050. The following conclusions can therefore be drawn:

- **Local hydrogen production and delivery is often competitive**, but depends on the availability of local, low-carbon and low-cost renewable electricity.
- **Ammonia shipping seems to be an interesting alternative** for intercontinental transport, especially when ammonia is the final use (e.g. in fertilizer industry). However, due to energy intensive reconversion, ammonia shipping for hydrogen end-use remains more expensive (almost +€1/kgH_2 for reconversion)[1].
- **Finally, hydrogen transport by pipeline remains the most economical solution**, especially for international-scale transport when H2 molecule is the final use.

Figures 6 and 7 show typical cost details for hydrogen transport and delivery by 2050 (all the figures are expressed in \$/kgH_2).

New intercontinental pipeline infrastructures could provide low-cost hydrogen to Europe by 2050. For example, pipelines between Russia and Germany or between Algeria and Spain will give the opportunity to Europe to dispose of hydrogen at a cost between €0.75/kg and €1.5/kg by 2050 (including production, transport and storage)[2]. These costs are expected to be lower than the low-carbon hydrogen that could be imported from Qatar via ships in 2050 (about €3.5/kg for British consumer) for example[2].

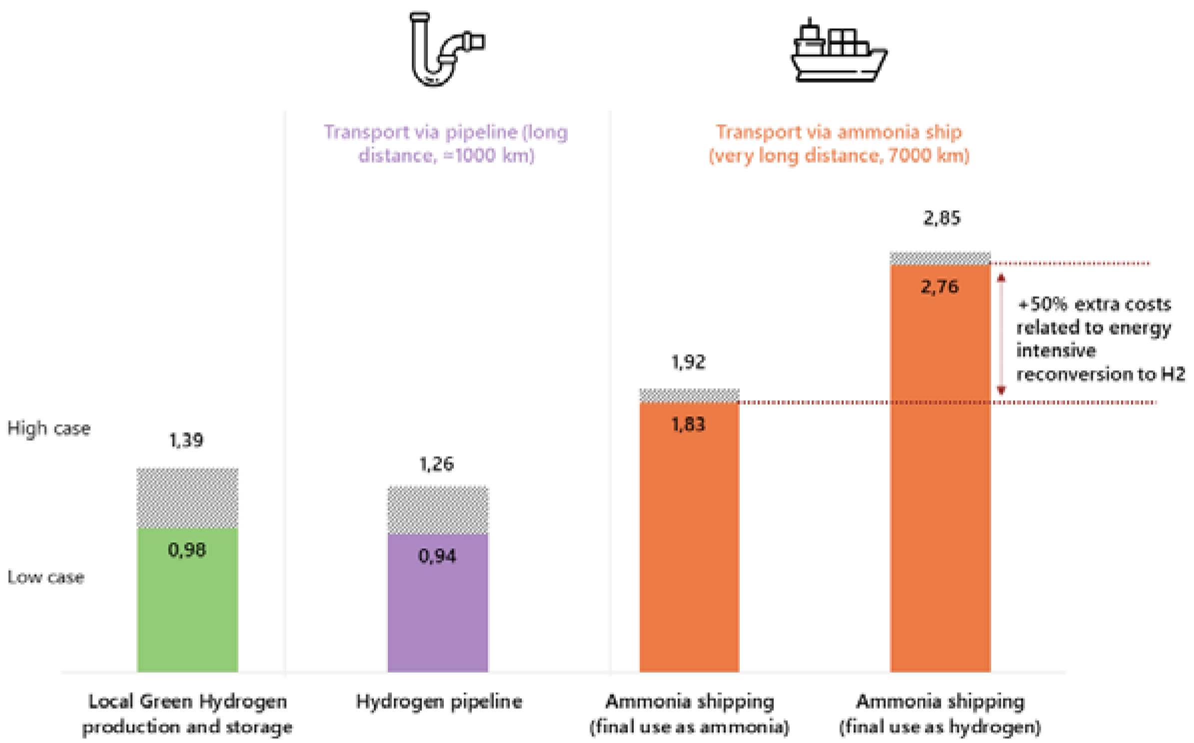

Fig. 6. Examples of all-in delivered costs (\$/kgH_2) by 2050, including production, transport and storage
(Source: Yélé Consulting, adapted from BloombergNEF, 2019 and Energy Transitions Commission, 2021)

Sources: [1] Energy Transition Commission, 2021; [2] BloombergNEF, 2019

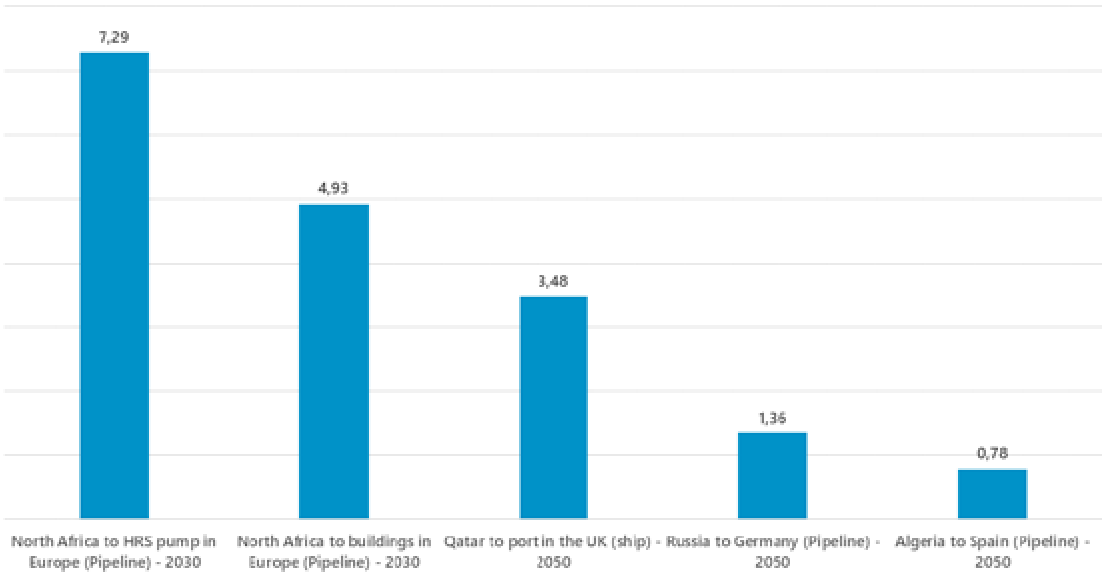

Fig. 7. Examples of levelised costs ($/kgH$_2$) of typical intercontinental transportation routes (Source: Energy Transitions Commission, 2021)

LARGE-SCALE HYDROGEN STORAGE

As for transportation, the **low-density of hydrogen makes it more difficult to store** than fossil energies (natural gas, oil, etc.). So far, hydrogen have mainly had captive uses, requiring extremely limited storage capacities. However, the emergence of a global hydrogen economy **will need a very significant storage capacity**. Being able to store the molecule in large quantities will be one of the most important challenges for the future of the clean hydrogen industry.

Here are some examples where hydrogen storage is essential:

- The development of **Hydrogen Refuelling Stations** (HRS) for road transport sector as well as for ports and airports.
- Several **industrial processes** (e.g. ammonia production, heating) where a **buffer stock is needed** to ensure a continuous process production.
- Integration of **inherently variable renewable electricity** (when supply exceeds demand) and participating in the power system balancing via the flexibility of electrolysers.

According to BloombergNEF[1], the storage capacity **needed is estimated at about 20% of annual hydrogen demand**. Therefore, two options are possible: disposing of very large-scale storage capacity or using compression technologies to store hydrogen in compressed gas or liquid form. Considering the costs of compression technologies (e.g. liquid storage technologies are often more expensive than hydrogen production), **large-scale geological storage will be the cornerstone** for the development of the future renewable and low-carbon hydrogen economy.

There are three types of geological storage:

- **Depleted oil and gas fields:** these fields could potentially provide large capacities for seasonal storage. However, the design of these fields could alter hydrogen purity, and therefore limit its applications. The technical and economic feasibility of this kind of storage is still being studied.
- **Rock caverns:** generally used to store Liquified Natural Gas, rock caverns could also represent a great alternative for hydrogen large-scale storage, even if the feasibility still needs to be verified for the storage of this energy carrier.
- **Salt caverns:** they are considered as the most relevant large-scale geological storage for hydrogen.

Source: [1] BloombergNEF, 2020

They have the capacity to provide low cost (around $0.11/ kg by 2050)[1] for storing and delivering large volume of hydrogen with a cycle period of 1 month. However, salt formations have limited geographical availability, and are concentrated in northern Europe at offshore and onshore locations. Germany accounts for the largest share, followed by the Netherlands, UK, Norway, Denmark and Poland. Other potential sites are located in France, Spain and Portugal.

Geological sites remain the most economical solutions for hydrogen large-scale storage. However, because of their limited availability and capacity, compressed storage technologies are also needed for the development of a future hydrogen economy.
As outlined in figure 9, the **availability of large-scale geological storage differs between regions**. While Europe and North America have the largest potential, countries with limited access to salt caverns (Middle East countries, South America, sub-Saharan Africa, ...) are more likely to rely on other storage technologies.

	STORAGE OPTION	VOLUME AND CYCLING	COST OF STORAGE ($/KG) FORECAST 2050	TRL	GEOGRAPHICAL AVAILABILITY
Gasseous state	Salt caverns	Large volumes, months-weeks	0.11	High	Limited
	Depleted gas fiels	Large volumes, seasonal	1.07	Low	Limited
	Rock caverns	Medium volumes, months-weeks	0.23	Low	Limited
	Pressurized containers	Small volumes, daily	0.17	High	Not limited
Liquid state	Liquid hydrogen	Small-medium volumes, days-weeks	0.95	Medium	Not limited
	Ammonia	Large volumes, months-weeks	0.87	High	Not limited
	LOHCs	Large volumes, months-weeks	2.86	Medium	Not limited
Solid state	Metal hybrides	Small volumes, days-weeks	Not evaluated	Medium	Not limited

Storage type : Geological Tanks

Fig. 8. Comparison of different storage options
(Source: Yélé Consulting, adapted from Energy Transitions Commission, 2021 and BloombergNEF, 2020)

Ammonia storage and transportation **FOCUS**

Ammonia benefits from **existing regulations** and **proven handling method for its transportation and storage** since dedicated pipelines already exist in industrial and maritime environments.

This energy carrier can be stored in a liquid state in two ways: it can be stored with an increased pressure at 0,99 MPa while maintaining temperature at the ambient level, or be stored at the atmospheric level with ammonia cooled down at -33.4°C[2].

Ammonia can be transported through tanker vessels, pipelines and tank-cars. The transportation is generally performed using a liquid form because of its significant higher density.

Sources: [1] Energy Transitions Commissions, 2021; [2] Ammonia Energy, 2014

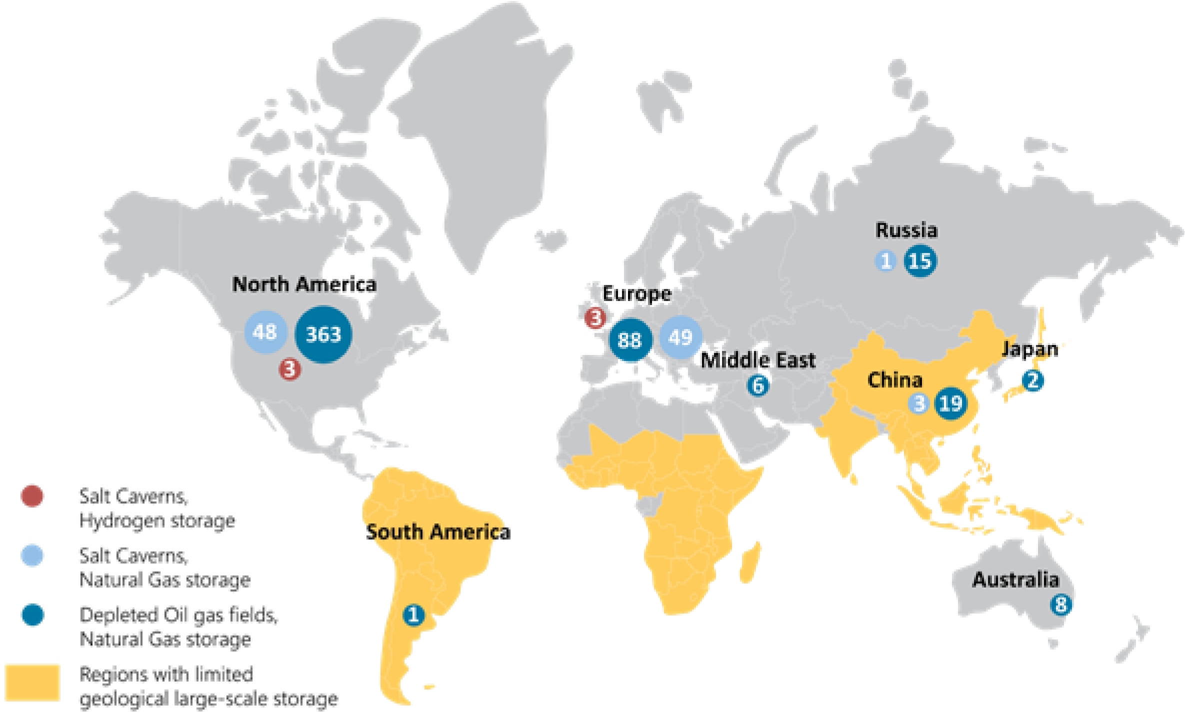

Fig. 9. Salt caverns and depleted gas fields across the globe
(Source: Yélé Consulting, adapted from Energy Transitions Commission, 2021 and BloombergNEF, 2020)

Renewable and low-carbon electricity transport as an alternative to the transport of H_2 molecules

Besides discussions on different means of transporting hydrogen and ammonia, **another model** is being considered today at the European scale: **transporting renewable and low-carbon electricity directly from favourable production locations to hydrogen consumption areas**. Indeed, the largest European hydrogen-consuming regions do not necessarily have a high penetration of RE. Therefore, there is a need to develop and reinforce European electricity grid, especially the interconnection capacity between countries, to allow for the transmission of low-cost electricity to hydrogen consumers that will then enable the molecule production near the consumption sites.

In this model, **electricity shall be transported via High-Voltage Direct Current (HVDC) lines since transportation costs decrease most importantly over longer distances than hydrogen pipelines**[1], where compressor stations are needed in regular intervals. Moreover, HVDC line costs are likely to decrease while pipeline technology disposes of a higher TRL with less cost reduction potential.

To efficiently support the development of the European energy system, the most economical model will depend on a number of factors and criteria, namely:

- **The end-use of hydrogen:** if hydrogen is needed for electricity production, it will always be more interesting to transmit the electricity directly to meet the need than to produce hydrogen, transport it before converting the molecule to electricity.
- **The possibility of hydrogen storage near the production area:** where possible, hydrogen pipelines is the most viable model since it takes advantage of the flexibility offered by the storage capacity.
- **The retrofit potential of existing natural gas transmission pipeline:** thanks to the reduced cost of using retrofitted pipelines, the all-in cost of the delivered hydrogen will decrease compared with using HVDC lines.

These infrastructure models **still need to be discussed with all the European stakeholders to fine-tune the economic, social and political stakes of each approach** and set the European ambition towards the development of hydrogen industry.

Source: [1] Energy Transitions Commission, 2021

In all cases, the **energy transition on the European level will not be affordable if only new infrastructure is built, whereas it could be a success if the overall energy system is adapted to integrate efficiently the most appropriate decarbonisation energy carriers.**

Coordinating the efforts at a European scale

A **global coordination at a European level for infrastructure development strategy is needed** as most countries have already started making their own move by funding different stakeholders of the new hydrogen value chain (producers, TSOs, DSOs, industrial manufacturers, end users, etc.) and building strategic partnerships.

For example, **France** is supporting the development of hydrogen hubs[1] with local production and end-use of the molecule, where low-carbon electricity is mainly provided by nuclear and hydro power plants. The French hydrogen strategy focuses on national industry development with limited consideration of partnerships outside the EU.

On the contrary, **Germany** is developing international partnerships (e.g. with Morocco)[2] and aims to export its technology while importing renewable hydrogen, methane and other synthetic fuels. The government holds that only renewable hydrogen is sustainable in the long term.

The coordination of these strategies should be supported by appropriate funding schemes (for example adopting the logic of IPCEI[3], Important Project of Common European Interest) that foster cooperation among countries and support the alignment of the different strategies and ambitions.

The development of this industrial vision will need to learn from previous intercontinental projects that have already failed to get off the ground such as the **Desertec** project (that intended to transport the solar energy of North Africa and Middle East before transporting it to Europe). Actors such as GRTGaz and Teréga, for example, have recently launched a public consultation (in June 2021)[4] to gather feedback on the needs and uncertainties around the future of the French hydrogen network.

Despite the multiple technologies and projects already studied and under experimentation, the European vision should be based on a **long-term vision** with **short-term decisions**. Indeed, decisions regarding investments need to be made in the short-term considering the time required (between 5 and 10 years) to deploy the energy infrastructures.

Even if newly built hydrogen pipelines could be relevant, it is necessary to consider the **conversion of already existing natural gas pipelines**, particularly since most of the potential hydrogen consumers are already connected to the existing gas grid, and some of them are considering the conversion of their processes to hydrogen.

Pending the pipelines' conversion, **blending hydrogen with natural gas** should be accelerated in the coming years to meet a potential short-term increase of hydrogen demand (especially for industrial and domestic heating). So far, blending hydrogen up to 20% on volumetric bases has required minimal or potentially no modifications to grid infrastructures. For example, the GRHYD project in France reached 20% blending in 2019[5], demonstrating the technical feasibility of this model, in particular for industrial end use. A similar experience is being conducted by H21 Leeds City Gate project that intends to progressively inject higher shares of hydrogen over time before the complete retrofit of existing networks.[6]

Sources: [1] French Ministry of the Economy, 2020; [2] Heinrich-Böll-Stiftung, 2021; [3] European Commission, 2021; [4] GRTgaz, 2021; [5] IEA, 2020; [6] H21 Leeds City Gate project, 2021

Developing a European hydrogen backbone[1]

FOCUS

The European Hydrogen Backbone (EHB) initiative consists of a growing group of **23 European gas infrastructure companies**, working together to plan the development of a dedicated hydrogen pipeline transport network spanning ten European countries.
By 2030, the EHB could consist of an initial **11 600 km pipeline network**, connecting emerging European hydrogen hubs. The hydrogen infrastructure can then grow to become a pan-European network, with a length of **39 700 km by 2040**. This approach is based on using 2/3 of retrofitted natural gas pipelines and 1/3 of newly built infrastructures, enabling a levelised transportation cost of €0.11 to €0.21 per kilogram of hydrogen.
A European Hydrogen Backbone is considered as essential to facilitate the creation of a European hydrogen Market and ensure that Europe becomes a climate-neutral continent. According to the report, EU and UK could see an increasing demand in the coming decades, reaching 2 300 TWh by 2050:

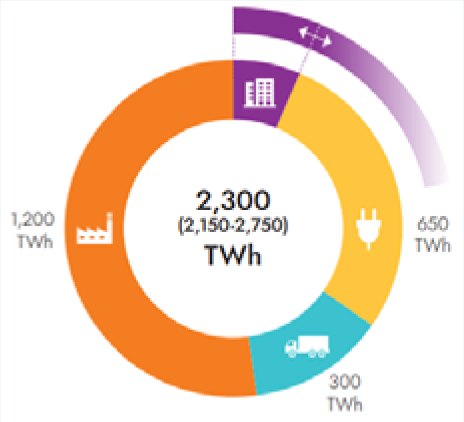

Fig. 10. Analysing future demand, supply, and transport of hydrogen (Source: Gas for Climate, 2021)

- **1 200 TWh** in **industry**, including 200 TWh of high temperature industrial heat.
- **650 TWh** of hydrogen for **electricity production**.
- **300 TWh** for **transport**, including the production of hydrogen-derived carriers.
- And finally, **150 TWh of hydrogen used in buildings** (assuming that total gas demand in building stock will be around 600 TWh by 2050).

Source: [1] Gas for Climate, 2021

Focus on some European projects and studies

Several European projects and studies have already been conducted to explore different possibilities regarding the **development of hydrogen distribution networks at a city level** and the emergence of **hydrogen transportation infrastructures at a European level**.

One of the studies that have been carried out was about the progressive conversion of the existing natural gas network of Leeds city (United Kingdom).

It should be highlighted that **hydrogen distribution networks** have already a **high TRL**. However, their potential remains questionable in a context where an integrated European hydrogen infrastructure is likely to emerge. A hybrid model could possibly be developed with local hydrogen valleys directly connected to the integrated networks.

The **social acceptability** and **security challenges** related to these networks are also important topics to address since hydrogen has always been an industrial molecule **very rarely used in urban environments**.

In addition, multiple initiatives have already been launched to support the development of hydrogen infrastructures. For example, **green investment bonds** have recently been launched by Northern Gas Networks (UK) to provide a public audience with the opportunity to invest in a hydrogen-ready network. Furthermore, Saudi Arabia is considering the implementation of a hydrogen pipeline between the Middle East and Europe, while Russia and Germany have considered the conversion of Nord Stream 2 into a hydrogen pipeline.

These complementary projects and initiatives are undoubtedly promising, but **they are not sufficient to trigger the transformation** of the European energy system towards a new hydrogen economy. The **establishment of a specific regulatory framework** is still needed to give visibility to TSOs and help them build consistent roadmaps for their future projects.

H21 Leeds City Gate project

FOCUS

The H21 Leeds City Gate project is a study whose purpose is to determine the economic and technical feasibility of **converting the existing gas network of Leeds to a 100% hydrogen network**.
This study outlined that:

- Existing **gas network has the appropriate capacity** allowing the conversion to 100% hydrogen pipelines.
- Conversion will need **minimal additional new infrastructures**.[1]
- Hydrogen can be gradually introduced in the existing network **without interruptions for customers** and that the existing demand for Leeds can be met with SMR production using CCUS technology and salt cavern storage.

According to the report, the project cost could have a limited impact on the customer gas bills if the funding is granted within the current UK regulatory business plan.

Fig. 11. H21 Leeds City Gate System Schematic
(Source: H21 Leeds City Gate project, 2021)

Sources: [1] H21 Leeds City Gate project, 2021

III. Studying a consistent European energy system: the LUT Energy System Transition Model

Aside from the interviews results and the state-of-the-art review, this study relies also on a **holistic modelling of Europe's energy system** that integrates a wide range of existing and future energy technologies with the most up-to-date knowledge and data. This part details the modelling methodology and some of its most relevant results.

MODELLING METHODOLOGY

The **LUT Energy System Transition Model** was applied across an integrated energy system covering demand from power, heat, and transport sectors, which enables the modelling of cost-optimal energy system transition pathways on high levels of geospatial (20 regions in Europe) and hourly resolutions. The capability to model at an hourly resolution for an entire year reveals crucial insights, particularly with respect to storage (including power-to-gas) and flexibility options.

The simulations are carried out in a two-stage approach. In the first stage, the prosumer simulations determine a cost-effective share of prosumers across Europe through the transition from 2020 to 2050, in five-year intervals.

In the second step, the energy modelling takes place: the **model integrates all crucial aspects of the power, heat, and transport sector demands**, while **the non-energetic feedstock for industry is not included in this simulation**. For every timestamp, the model defines a cost-optimal energy system structure and operation mode.

A previous version of this model has already been used by LUT University and SolarPower Europe to carry out the 100% Renewable Europe study. Specific developments - related to hydrogen sector - have been made on the model within the scope of this study.

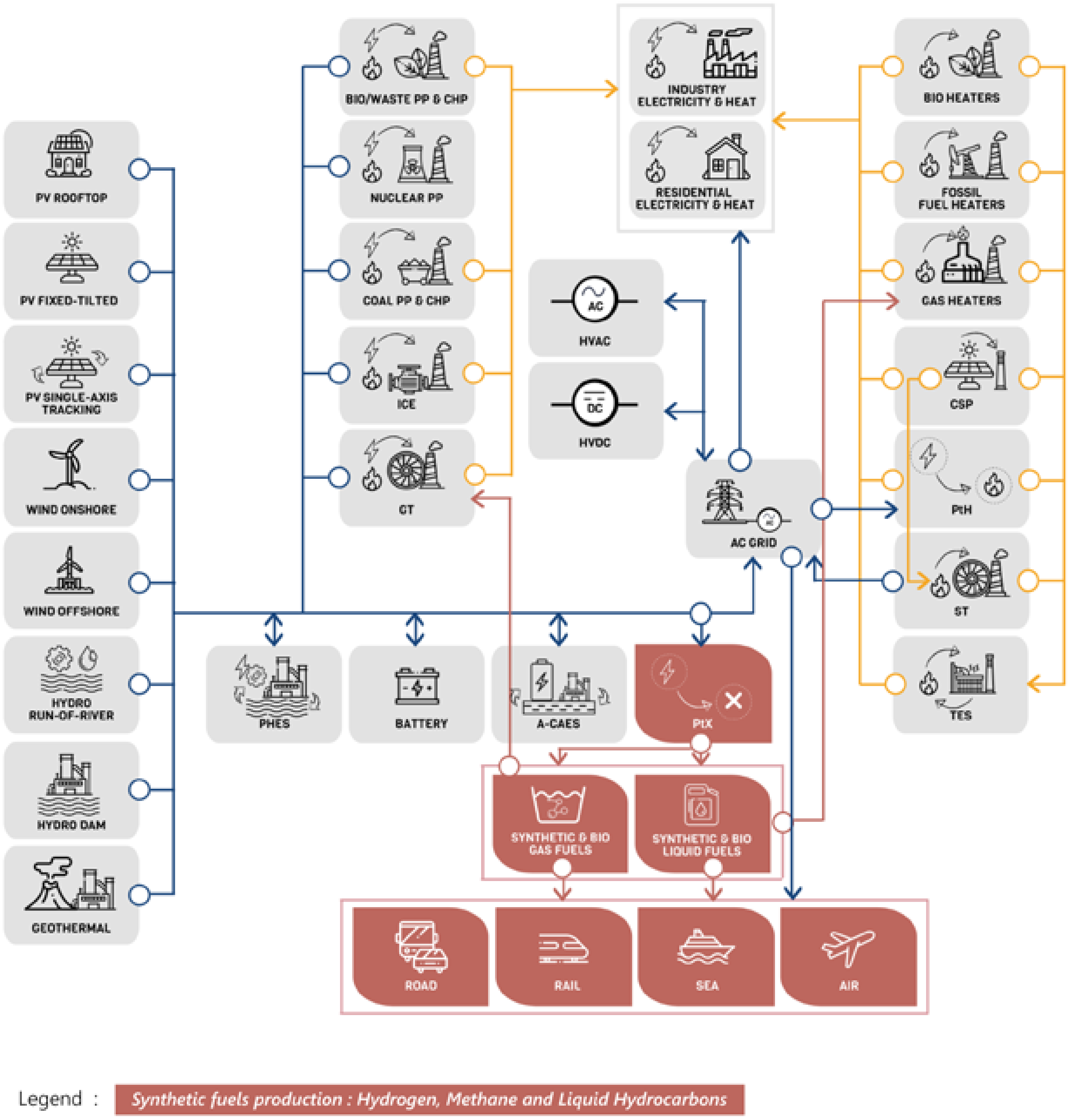

Fig. 12. Used energy system transition model
(Source: LUT University and Yélé Consulting)

LUT Energy System Transition Model

The model consists in a multi-energy approach that **integrates the entire value chains of power, heat, transport and industry sectors**. A strong consideration is given to all kinds of **power-to-X applications:** mobility, heat, e-fuels, chemicals, seawater desalination, CO_2 sequestration, etc.
For every timestamp, the model sets a cost-optimal energy system structure and operation mode.

The target of the optimisation is to minimize the total cost of the energy system on each step of the transition.

The system can produce hydrogen, methane and liquid fuels (diesel, gasoline, jet fuels) to **substitute the use of fossil fuels in the power, heat, transport sectors and industry**. Hydrogen can be produced from fossil methane via steam reforming (CO_2 can be discharged to the atmosphere or captured and stored) or from water electrolysis. The production process of synthetic fuels is modelled in figure 13.

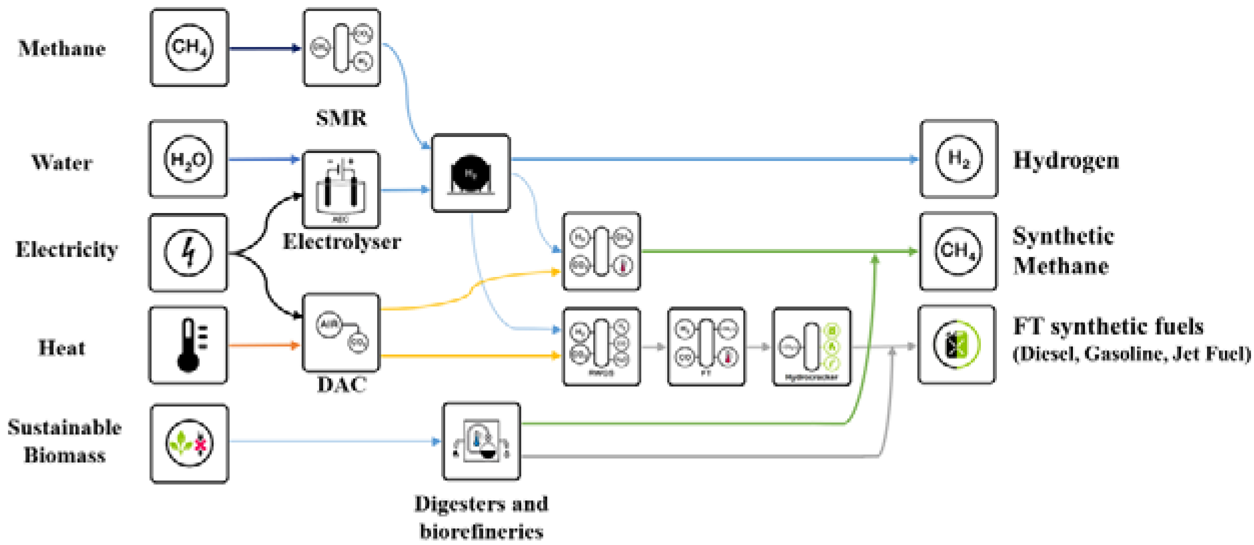

Fig. 13. Synthetic fuels production in the model
(Source: LUT University and Yélé Consulting)

Regional composition

The European energy system is structured into 20 sub-regions grouped into **4 macro regions and Iceland**. The composition of the regions is as follows:

- **Nordic:** Norway, Denmark, Sweden, Finland, and Baltic region (Estonia, Latvia and Lithuania),
- **West:** Iberian Peninsula region (Portugal, Spain and Gibraltar), France (including Monaco and Andorra), British Isles region (United Kingdom and Ireland) and Benelux region (Belgium, Netherlands and Luxembourg);
- **Central:** Germany, Poland, CRS (Czech Republic and Slovakia), AUH (Austria and Hungary) and region with Switzerland and Liechtenstein;
- **Southeast:** Italy (together with San Marino, Vatican and Malta), the Western Balkan countries (Slovenia, Croatia, Bosnia and Herzegovina, Kosovo, Serbia, Montenegro, Macedonia, Albania), the Eastern Balkan countries (Romania, Bulgaria and Greece), UA (Ukraine and Moldova) and TR (Turkey and Cyprus)
- **Iceland**, as an isolated region.

Fig. 14. Composition of the regions modelled
(Source: LUT University and Yélé Consulting)

Modelling scenarios

In the context of achieving the goals of the Paris Agreement in a technically feasible and economically viable way, three distinct scenarios are modelled for an integrated energy sector, combining the power, heat, and transport demands for the case of Europe (full description of the scenarios is available in the annexes).

In addition, to dedicate more attention to the potential role of hydrogen in the energy system and perform sensitivity analyses, two specific scenarios have been built and studied within the framework of this study:

- **Moderate scenario with increased hydrogen consumption:** the European energy system remains very similar to the moderate scenario. The shares of hydrogen for transport sector are increased to model a growing demand between 2020 and 2050. The details of the assumptions are set out in the annex.
- **Moderate scenario with increased low-carbon hydrogen production:** for this scenario, in addition to renewable hydrogen, the molecule can be produced through Steam Methane Reforming process (SMR) with the possibility of using carbon capture, transport and storage (CCTS), in order to analyse the competitivity between renewable hydrogen and low-carbon hydrogen. The details of the assumptions are set out in the annex.

	LAGGARD	MODERATE	LEADERSHIP
AMBITION PATHWAY	Minimum	Minimum	High
EC CLIMATE NEUTRALITY	Not achieved	Achieved by 2050	Achieved by 2040
FOSSIL FUEL	No phase-out	Phase-out by 2050	Phase-out by 2040
REDUCTION IN GHG EMISSIONS	Around 80% by 2050	100% by 2050	100% by 2040
GHG EMISSION COST	Minimum €150/tCO_2 by 2050	Minimum €150/tCO_2 by 2050	High €200/tCO_2 by 2050
GLOBAL PARIS AGREEMENT	Not achieved	Achieved 1.5°C - 2°C	Achieved with high ambition 1.5°C

Fig. 15. Description of the studied scenarios
(as modeled in the "100% Renewable Europe" study conducted by SolarPower Europe)

MODELLING RESULTS

Sector coupling and the role of power-to-X technologies in reducing GHG emissions in European energy sector

Based on the several scenarios and assumptions detailed above, the modelling results highlight **the need for Europe to make the transition from a centralised and largely decoupled energy system - relying on imported fossil fuels - to an integrated one**, where the plurality of energy sectors (power, heat and transport) are coupled on basis of direct and indirect electrification.

Sector coupling is thus a key enabler to reduce GHG emissions in the European energy sector. It depends on the integration of several energy infrastructures and carriers - electricity, heat and synthetic fuels - and the deployment of different power-to-X technologies (power-to-gas, power-to-fuel, power-to-heat, etc.). **The greater the number of power-to-X projects the higher the degree of sector coupling.**

Therefore, hydrogen is part of a complex and integrated energy system and cannot be treated separately. In particular, renewable electricity-based hydrogen emerges as one of the most important energy carriers through the transition, mainly used for the production of synthetic fuels (gas and liquid fuels).

While using direct electricity is an efficient solution in a number of cases, **it is difficult to completely replace fuel use in certain applications** (high temperature industrial heating, maritime transport, aviation, chemical feedstock). Also, the current road fleet is largely based on internal combustion engines vehicles, and replacing them with electric vehicles is still a number of years away.

To overcome this challenge, **hydrogen plays an important role as an energy carrier for the development of synthetic fuels** (with equivalent chemical features to hydrocarbon fuels). From 2030 onwards, renewable hydrogen contributes to the full decarbonisation of the heat and transport sectors, becoming **Europe's second key energy carrier** (behind electricity). This is enabled by a massive deployment of low-cost solar and wind power as prime energy carriers, setting the direction towards a truly decentralised, flexible, and demand-driven energy system.
The impacts of sector coupling in the Moderate scenario are highlighted in figure 16, which shows the energy flows of a fully sector-coupled European energy system in 2050, compared to its decoupled status in 2020. This scenario presents a variety of flexibility options, including a mix of power-to-heat, power-to-gas and power-to-liquid fuels. Almost 6 000 TWh of renewable electricity is transformed to synthetic fuels (via electrolysis and hydrogen production) to decarbonise transport and heat sectors.

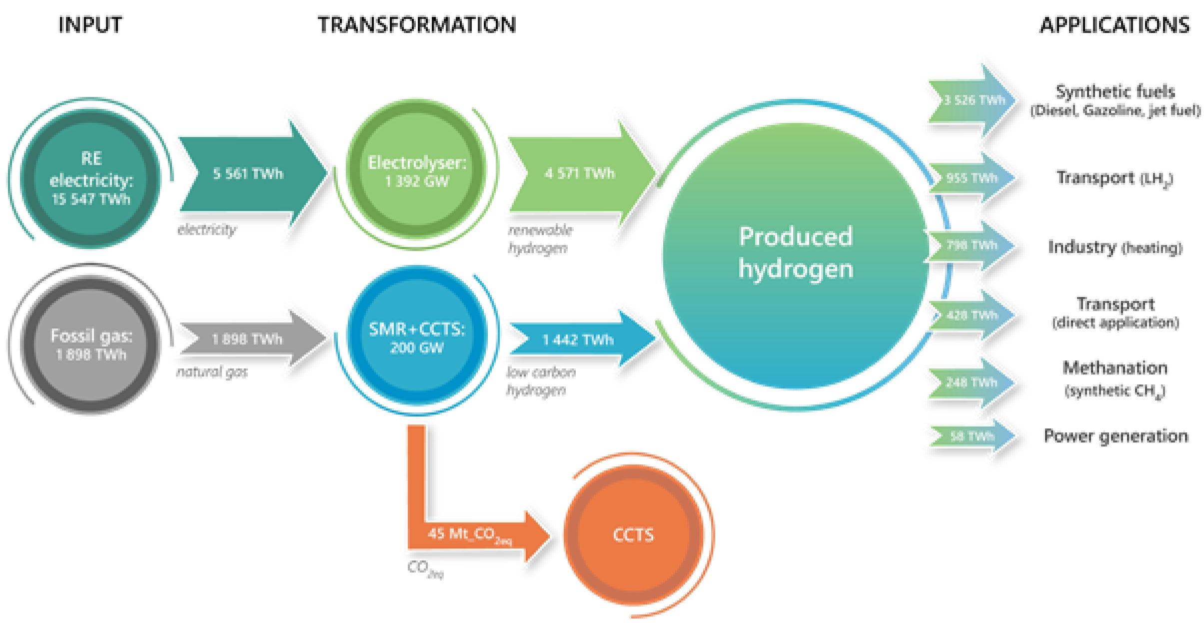

Fig. 16. Integration of hydrogen into the European energy system
(Source: LUT University and Yélé Consulting, results of the low natural gas price scenario)

Renewable and low-carbon hydrogen production

As illustrated above, sector coupling allows the production of two types of hydrogen: renewable hydrogen, produced via water electrolysis using renewable electricity; and low-carbon hydrogen, through Steam Methane Reforming process (SMR) and carbon capture, transport and storage (CCTS) technology.
With the given assumptions (see annex), the model reveals that **SMR+CCTS is not competitive compared to water electrolysis technology** due to the abundance of low-cost electricity in a RE-based energy system (with electricity as an input in electrolysers) and the revenue that can be gained from flexibility services provided by electrolysers. Thus, **water electrolysis dominates the hydrogen production between 2030 and 2050**. The role of **low-carbon hydrogen in the European energy system remains minor compared with renewable-based production**. Its production increases through the transition until 2045 (peak at 1468 TWh), but its relative share reaches its maximum in 2040 (35%) and later continuously declines due to rising hydrogen production from electrolysis. In 2050, SMR + CCTS provides almost 25% of hydrogen in the system in a low-cost NG scenario, but only 5% in a scenario with moderate rising Natural Gas (NG) prices.

Low-carbon hydrogen can find a niche in the market if natural gas cost is low and if hydrogen storage is significantly higher than traditional methane storage. Its **main role in 2050 energy system is to provide base supply of hydrogen and increase the flexibility of electrolysers**.
It should be noted that the results are based on an analysis performed at a European level and that the **outcomes could differ according to the local specificities of each country**.

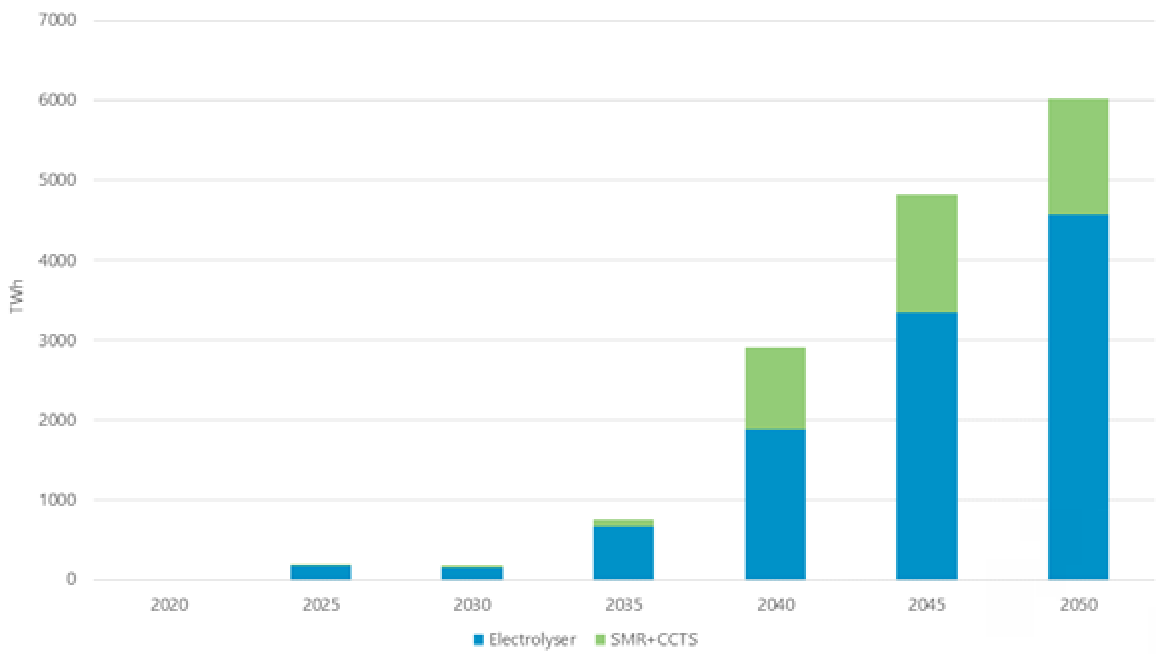

Fig. 17. Production of renewable and low-carbon hydrogen at European scale in a low-cost natural gas scenario
(Source: LUT University and Yélé Consulting, results of the low natural gas price scenario)

Hydrogen and synthetic fuels for transportation

In 2020, the transport sector shows a very limited renewable energy share compared to other sectors (only 5% of the energy is provided by renewables) and is responsible of almost 25% of Europe's GHG emissions.

Unlike with the heat sector, the share of fossil fuel consumption in the transport sector will remain high in 2030. **The rapid decrease down to zero in the Leadership scenario will take place starting from 2040, when renewable electricity-based synthetic fuels reach their full potential.** As detailed in figure 18, the main contributor to replace fossil fuels will be Fisher-Tropsch (FT) fuels (power-to-liquid technology for synthetic fuel production - such as diesel, gasoline, jet fuel from hydrogen – and CO_2).

Hydrogen will also be used as a fuel for transport, which will be **one of the three major pillars** (with electricity and FT fuels) in final energy demand by 2050 (Moderate and Leadership 100% renewable scenarios).

In summary, renewable electricity will drive the transition initially (2020-2030) and from 2030 onwards RE-based hydrogen and FT fuels becomes technologically and economically ready to take over and substitute fossil fuels in the applications where direct electrification is not possible across the three scenarios. **The role of hydrogen and RE-based FT fuels is vital to support the transition of transport modes that cannot be directly electrified** (in particular marine and aviation sectors).

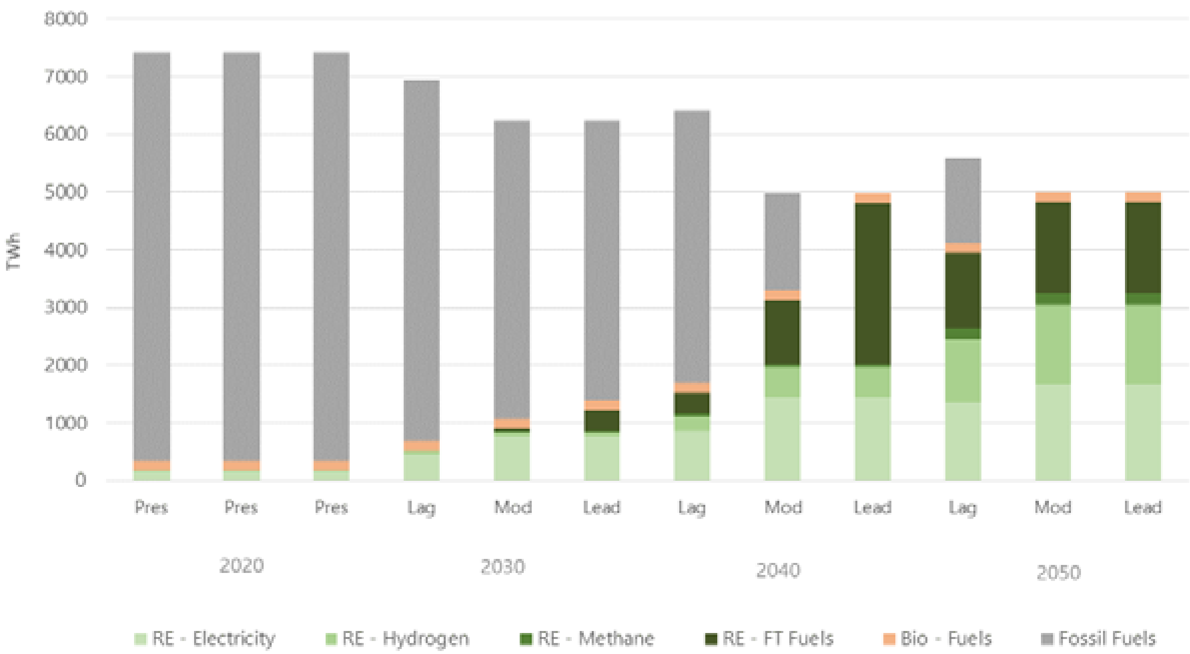

Fig. 18. Final energy demand (fuel use) for transport
(Source: LUT University and Yélé Consulting, results of themoderate scenario modeled in the "100% Renewable Europe" study conducted by SolarPower Europe)

Hydrogen for renewable heat generation

Heat is mainly used in industrial processes, space heating and domestic hot water. In 2020, the heat market is strongly dominated by fossil gas, oil and coal. Only about 23% of heat is provided by renewables (mostly from bioenergy).

According to the scenarios analysed, the transition to a low-carbon heat generation by 2050 will be reached mainly through **renewable-based electric heating** (direct heating) and **heat pumps** (indirect heating).

However, **all three scenarios outlined a notable portion of renewable-based synthetic fuels** (based on hydrogen and methane) in the heat generation mix, which will play a crucial role in industrial heat process decarbonisation (that otherwise would rely on fossil fuels).

Throughout the energy transition, **renewable electricity and hydrogen will deliver most of the heat**: RE-based hydrogen **will be developed** from 2040 (15% of the consumed electricity for heat production), while RE-based methane emerges later to accelerate the phase-out of natural gas-fuelled heating.

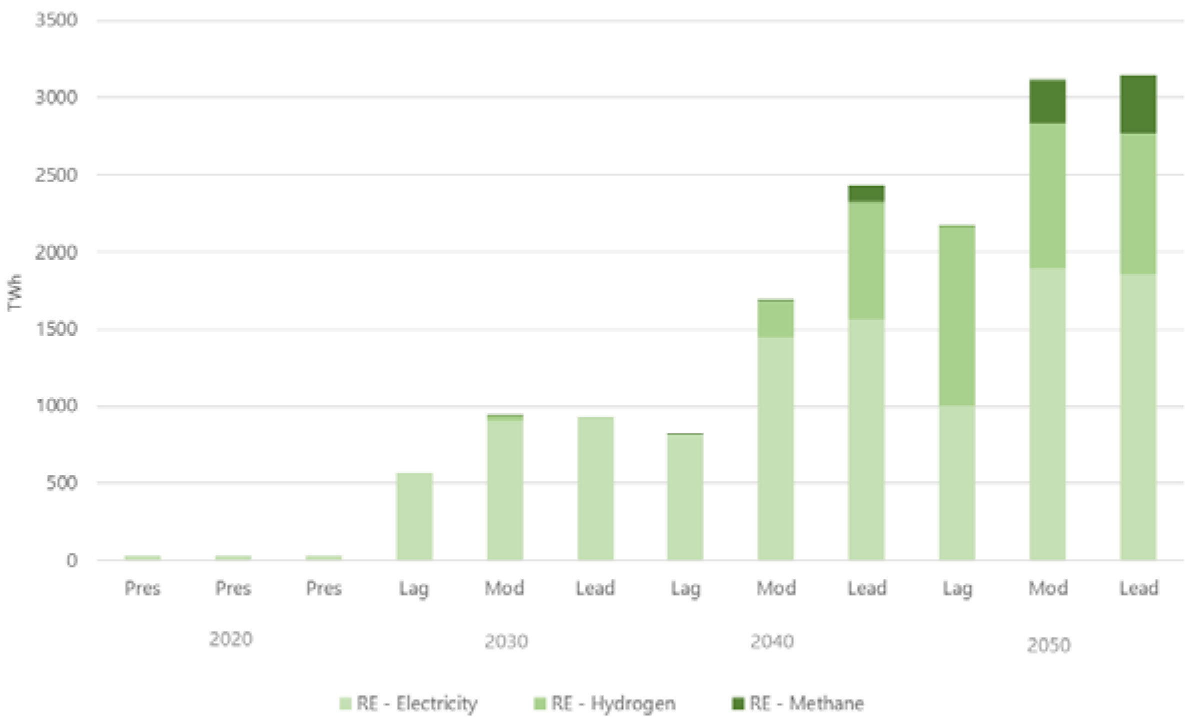

Fig. 19. Electricity demand for sustainable heat
(Source: UT University and Yélé Consulting, results of the moderate scenario modeled in the "100% Renewable Europe" study conducted by SolarPower Europe)

Hydrogen development across Europe

As shown in the previous analysis, **electrolyser technology is crucial to support the development of a decarbonised European energy system by 2050**. It will not only enhance the flexibility of the energy system and the integration of renewable energies but will also enable the production of synthetic fuels (hydrogen, renewable methane and FT-fuels) to decarbonise industry, transport and heat sectors.

Based on the analysed scenarios, electrolysers' installed capacities will be distributed across Europe, with the **higher capacities operating in Iberia (Spain and Portugal) and Turkey**. Overall, 1 392 GW of electrolyser capacity will be installed by 2050 to produce 76% of the needed hydrogen in order to decarbonize the European energy system.

To feed the electrolysers' capacity mentioned above, low-cost and low-carbon renewable electricity is needed across the several European regions. The analysis showed that by 2050, the average LCOE for the studied scenarios are essentially the same: **€36.9/MWh for the Moderate and €39.4/MWh for the Leadership scenario**.
This cost includes production unit CAPEX and OPEX, grid costs and GHG emission costs.

However, there are **significant regional differences in the LCOE**, with southern countries showing lower electricity production costs due to a higher share of utility-scale solar systems, which can generate power at a very low cost in the right conditions. For example, the **LCOE for producing renewable electricity in Iberia and Turkey falls below €20/MWh**, which also explains the higher share of electrolyser capacities in these regions.

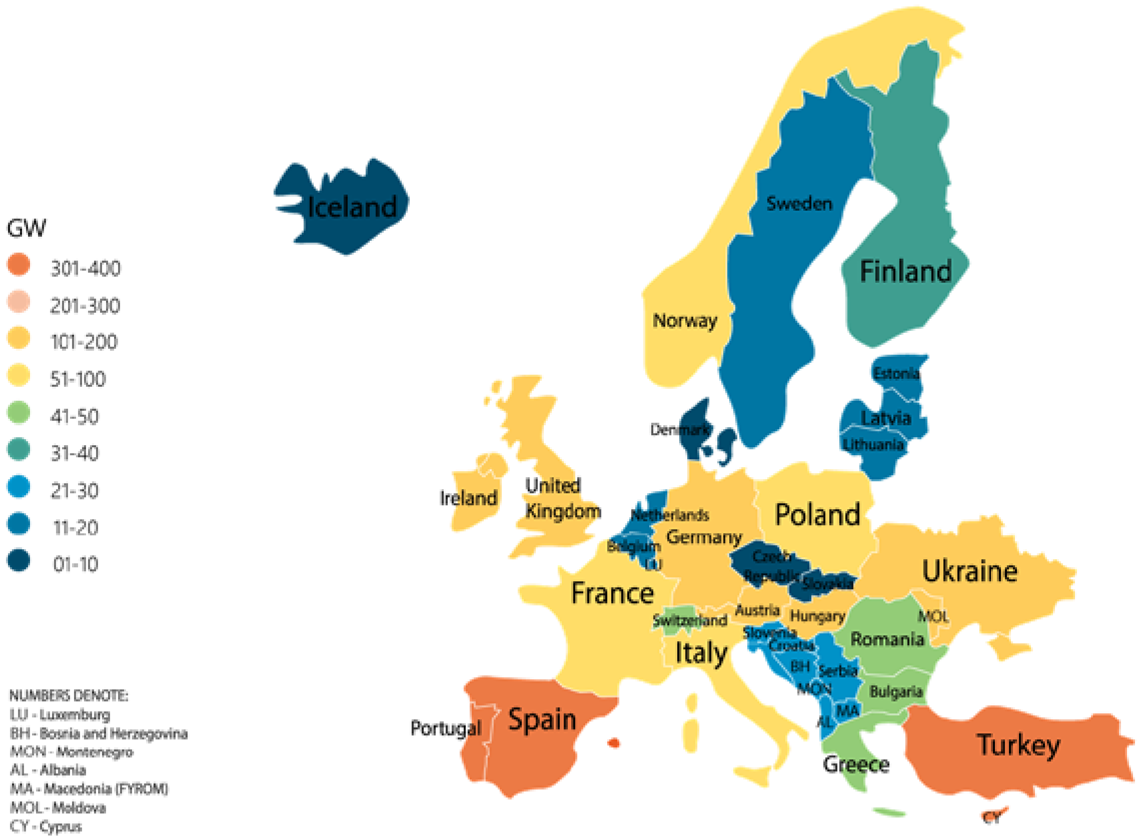

Fig. 20. Regional electrolyser capacity across Europe in 2050
(Source: LUT University and Yélé Consulting, results of the moderate scenario)

Fig. 21. Levelised cost of electricity across Europe in 2050
(Source: LUT University and Yélé Consulting, results of the moderate scenario)

IV. Recommendations for a strong European hydrogen economy

THE KEY ROLE OF THE EUROPEAN COMMISSION

Europe must structure its efforts to assert its leadership: while the hydrogen economy appears to get off to a good start, **national governments and European institutions have a critical role to play to ensure its sustainable development**. In its 2020 H_2 strategy, the European Union clearly emphasizes the need for international cooperation to support hydrogen development in order to achieve its ambitious goals by 2050.

Once clear targets, strategic investments and fiscal incentives are established, **the market will be able to send the right signals for the private sector to invest in infrastructure, emerging technologies and new business models**.

In light of the **solar power industry pitfall 10 years ago**, maintaining a competitive technical industry is critical to ensure European leadership in hydrogen development. Key to this will be cooperation between European states to develop joint projects and initiatives.

There is a risk that if each country sets out its own roadmap to reach goals defined at a European level, there will be a missed opportunity for knowledge and capability sharing across Europe which would slow the development of the hydrogen economy.

A strong European governance is needed to **boost faith in political commitments** and to **reassure industrials and private sectors** by communicating clear perspectives regarding funding schemes.

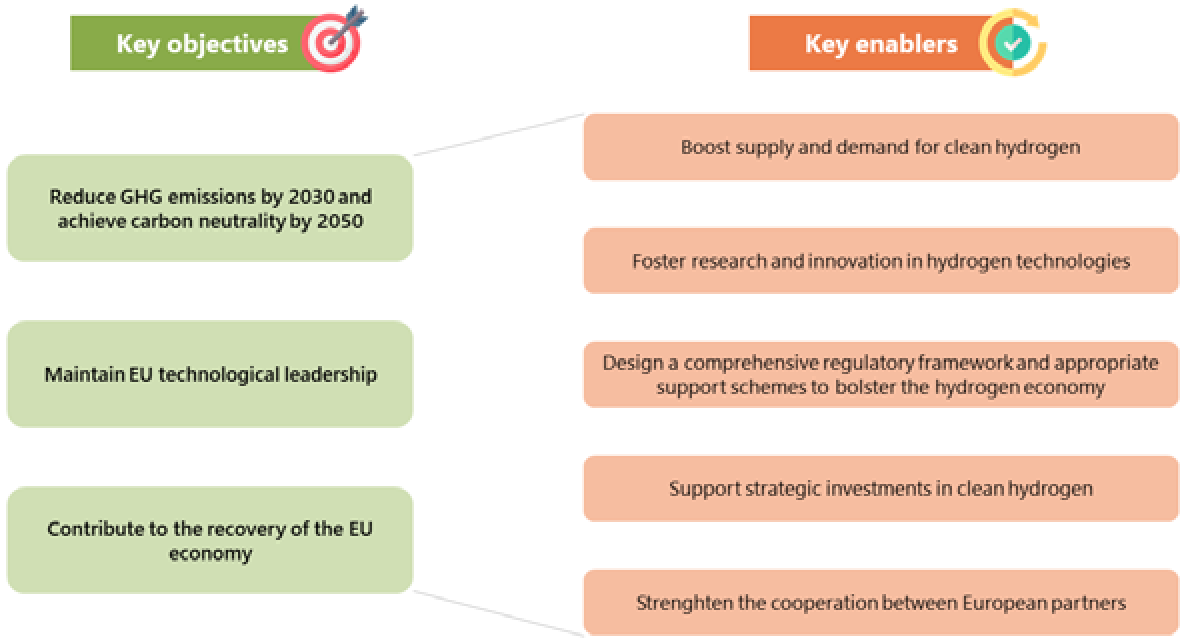

Fig. 22. EU hydrogen roadmap to 2050
(Source: Yélé Consulting, adapted from European Commission, 2020)

A SHARED OBJECTIVE, BUT DIFFERENT ROADMAPS TO REACH IT

Many states decided to seize the momentum around hydrogen in 2020 and published **ambitious national strategies and roadmaps**[1]. However, **the approach as well as the strategic goals differ from one plan to another**, as each country put forward their existing assets for switching to a clean hydrogen economy. In this part, a focus will be made on the **most promising European national strategies**, namely France, Germany, Spain and Norway.

FRANCE[2]

€7.2 Bn
Pledged by 2030

6,5 GW
electrolyser capacity by 2030

€30-40/MWh
expected LCOE by 2050[3]

Fostering local development

The government's primary focus is to support R&D&I and to establish a hydrogen value chain in France. Extensive infrastructures and a low-carbon electric mix will facilitate the implementation of low-carbon hydrogen. The French hydrogen strategy mainly focuses on the national situation: no partnerships outside the EU are yet considered and no support measures are implemented to foster the development of a global market.

The French strategy aims to :

- Strengthen the French industrial and economic position as well as its energy sovereignty.
- Decarbonise the French industry and promote clean mobility.
- Support French companies throughout the entire hydrogen value chain.

GERMANY[4]

€9 Bn
Pledged by 2030

5 GW
electrolyser capacity by 2030

€40-50/MWh
expected LCOE by 2050[3]

Bolster partnerships

Establishing international partnerships (starting with North Africa) is the main priority for the German Federal Government. Germany aims to export its technology while importing renewable electricity, hydrogen, methane and other synthetic downstream products.
The German hydrogen sector benefits from a large volume of funding and a sophisticated governance structure.

The German strategy aims to :

- Became a world leader.
- Establish partnerships, encourage international trade and develop a global market.
- Fulfil international sustainable development goals and achieve carbon neutrality.

Sources: [1] Yélé Consulting, 2020; [2] French National Hydrogen Strategy, 2020; [3] LUT, 2021; [4] German National Hydrogen Strategy, 2020

NORWAY[1]

N/A
Pledged by 2030

N/A
electrolyser capacity by 2030

€40-50/MWh
expected LCOE by 2050[2]

Make the most of the gas infrastructure with low-carbon hydrogen

Norway will focus specifically on its maritime industry, in order to keep its international pioneering role in green shipping. The government sheds light on blue hydrogen in order to strenghten the Norwegian gas industry and its opportunities throughout Europe. The strategy has not pledged any budget or electrolysis capacity by 2030. A more detailed roadmap is expected by the end of 2021.

The Norwegian strategy aims to :

- Support technology development and enhance industrial competitiveness.
- Rely on their maritime assets to remain a green shipping pioneer.
- Develop low-carbon hydrogen alongside with natural gas.

SPAIN[3]

€9 Bn
Pledged by 2030

4 GW
electrolyser capacity by 2030

€20-30/MWh
expected LCOE by 2050[2]

The renewable champion

The government wants to build on EU cooperation and aims to tap into its great low-cost renewable potential to export renewable hydrogen to European countries. Moreover, the government believes that hydrogen is a key factor to facilitate the integration of Spain's renewable electricity production (solar and onshore/ offshore wind power). Spain mainly relies on private investments (no dedicated public hydrogen fund).

The Spanish strategy aims to :

- Support research, development and innovation to develop new technologies.
- Produce renewable hydrogen and support the integration of low-cost renewable electricity.
- Have a leading role in the European hydrogen market.

Boost competitiveness with the HyDeal Ambition project

FOCUS

The HyDeal Ambition collective aims to create a **leading European hydrogen economy enabling renewable hydrogen production at €1.5/kg before 2030 (transport and storage included[4])**.

The project gathers over +30 energy industrials. With 95 GW solar capacity located in Iberia and dedicated to hydrogen through electrolysis, the group aims to produce 3.6 Mt of renewable hydrogen per year.

Although the targeted price of €1.5/kg is being controverted, the project is a first of its kind, proving that **cooperation is key to reach competitiveness**.

Sources: [1] Norwegian Government's hydrogen strategy, 2020; [2] LUT, 2021;
[3] Spanish National Hydrogen Roadmap, 2020; [4] DH2 energy, HyDeal Ambition, 2021

ENABLING A REGULATORY FRAMEWORK UNDERPINNING THE MARKET

This study shed light on the **importance of regulation and adequate policies** to foster the development of clean hydrogen within a net-zero emissions economy by 2050: **national regulations must align** to reach the ambitious European objectives. As market will dictate the transformation, **incentivising demand side should be a priority** objective to allow the private sector to switch to hydrogen-powered solutions.

Within the past two years, several European policymakers have set the pace for clean hydrogen development by publishing national hydrogen strategies and roadmaps. However, the **current regulatory framework still lacks specific tools** to allow a true hydrogen scale-up, and more generally decarbonising solutions to compete with existing carbon-intensive processes. The much-awaited "**Fit for 55**" policy packages released in July 2021 should provide a great opportunity to transform the European energy system policies to integrate those considerations[1].

At least **4 priority regulatory issues** seem critical to be addressed in order to enable a net-zero emission energy system based on a sustainable hydrogen economy:

- **Incentivise carbon abatement technologies and uses:** today, the CO_2 prices set by the existing markets and pricing mechanisms – such as EU ETS or national carbon taxes – are too low to favor a scale-up of carbon abatement options such as renewable hydrogen or CCS. Numerous studies agree that a sharp increase in CO_2 pricing is critical to the development of a net-zero economy: the 2019 reviewed Quinet report[2] on state-imposed carbon value recommended a price of **€250/ tCO_2 in 2030 increasing to €600-900/tCO_2 in 2050** in order to reach the net-zero threshold. The **incoming reform of the EU-ETS is an opportunity to include new energy carriers** as well as new sectors, allowing a more comprehensive carbon market and a faster transition to low-carbon solutions. As the **EU-ETS reform might not be sufficient to boost the renewable hydrogen economy**, other schemes can be activated to improve the competitiveness of renewable hydrogen, in line with the **ReFuelEU Aviation** and the **FuelEU Maritime** initiatives as well as with **the Energy Taxation Directive**. Such schemes can be completed by various incentive mechanisms[1] such as feed-in tariffs, technology-oriented subsidies or carbon Contracts for Difference (CfD)[3].
- **Foster innovation and research on the supply side to help reach viable business models**, such as targeted in the European hydrogen strategy. Apart from the alkaline electrolysis process, most of the technologies that renewable hydrogen system rely on are at **their early stages** (salt cavern storage at TRL 5-7[4], Solid Oxyde Electrolysis at TRL 6[5]) and **need financial support to enhance the competitiveness** of renewable and low-carbon hydrogen. Such support can be provided under different forms, such as the **Innovation Fund or the Horizon Europe program**. The IPCEI Hydrogen, adopted in 2020, is a huge step in that direction.
- **Ensure bankability of investments in clean hydrogen projects:** for instance, ArcelorMittal estimated that the overall energy transition of steelmaking industry would cost approximately €10-20bn[6]. Similar investments are required all along the demand side to switch to renewable hydrogen solutions. Mitigating the financial risks and developing a further consistent regulatory framework are key to help investors have a clearer view of the market. The "Fit for 55" legislative package is expected to lift the veil on the underlying uncertainties. Public financial institutions will play a core role in providing access to low-cost investments through facilities such as the numerous national Covid recovery plans, the Modernization Fund[7] or the Just Transition Fund[8].

Sources: [1] European Commission, 2021; [2] France Strategy, 2019; [3] IDDRI, 2019;
[4] Mariana Barbero Ribeiro Goulart et al., May 2020; [5] Store&Go, 2019; [6] ArcelorMittal, 2021;
[7] European Commission, 2020; [8] European Commission, 2020

- **Support the development of an organised hydrogen market:** in addition to boosting demand and supply sides, developing a fully functional hydrogen market is vital for the establishment of a future hydrogen economy. The basics of such a market have already been explored by various European TSOs and are yet to be discussed. Timing is everything, as it is important to make the most out of the hydrogen momentum and set, at the right pace, the building blocks of a European organised market. The revision of the energy package for gas and its extension to renewable gases is a milestone for the hydrogen regulatory framework and is expected to lay the foundations of this upcoming market.

Defining the nature of hydrogen produced using grid electricity

FOCUS

Aside from producing hydrogen using renewable electricity, hydrogen can also be produced from grid electricity. However, electricity has a **very different carbon footprint across Europe**. Producing hydrogen using grid electricity would make sense in **low-carbon electricity regions**, such as Norway or France (eg. 40-60 gCO_2/kWh), where hydrogen could be qualified as "low-carbon". However, grid-based hydrogen production would not be relevant – if not counter-productive – in regions where electricity is more carbon intensive, such as Germany or Poland (eg. 400-600 gCO_2/kWh).
Using the grid electricity to fuel electrolysers could be an effective short-term boost for the hydrogen economy, but the sector lacks a regulatory framework: there is a **need to define a clear carbon footprint threshold** for low-carbon hydrogen production as well as a clear European standards and classification terminology.
Such normalisation work has already started by the **CertifHy project**[1] supported by the European Commission, which provides a solid ground to define standards for low-carbon hydrogen in terms of lifecycle GHG emissions. The threshold has initially been set at **4.4 $kgCO_2/kgH_2$** - 60% of grey hydrogen levels - in order to enable SMR+CCUS facilities to be considered.
Furthermore, the **current EU taxonomy policy** advocates for a lower threshold of **2.3 $kgCO_2/kgH_2$**. In order to be below this limit, the carbon intensity of electricity used for electrolysis should be less than **45 gCO_2/kWh**[2]. It should be noticed that most European grids are currently above this limit, therefore huge efforts should be undertaken in the short term to fast decarbonisation of the power system and enable grid-based low-carbon hydrogen production.

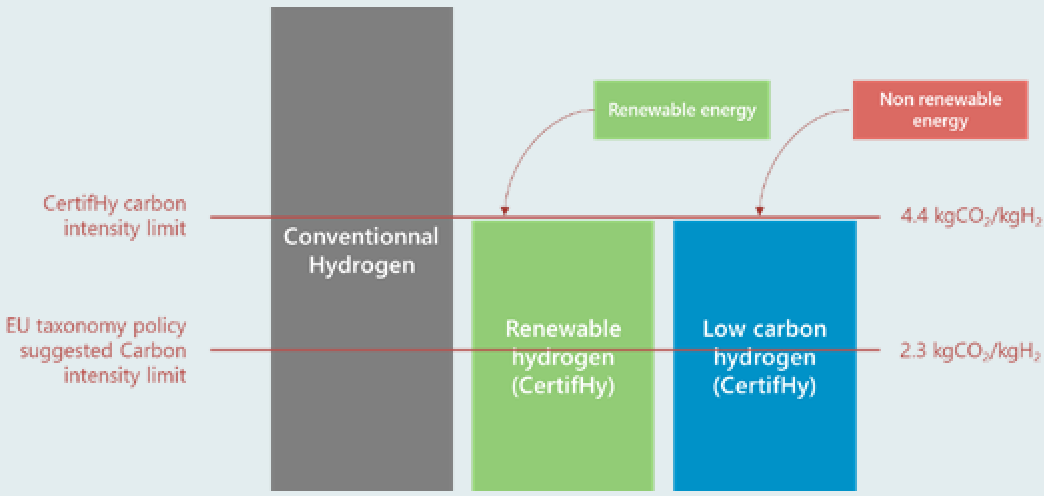

Fig. 23. Thresholds for "low-carbon" hydrogen denomination, adapted from the CertifHy project

Sources: [1] FCH JU, 2018; [2] European Commission, 2020

SHORT-TERM ENABLERS TO ALLOW THE EMERGENCE OF LOCAL HYDROGEN PROJECTS

Before clean hydrogen could be developed on a European scale, some requirements must be tackled to make possible the scale-up of the projects. These requirements include:

- **Grant access to low-cost renewable electricity:** the cost of renewable hydrogen projects mainly consists in electricity supply cost, which represents 60-70%[1] of the total costs. Contrary to what might be assumed, technological advances and CAPEX reduction will not alone solve the economic issue of the emerging industry. **Granting access to low-cost and low-carbon electricity is a key enabler for clean hydrogen development.** This could be accelerated by the development of specific market mechanisms - such as Power Purchase Agreements (PPA) or Guarantees of Origin (GO) - that will facilitate the sourcing of renewable and low-cost electricity. Lowering the price of renewable electricity and bolstering its integration in the grid is therefore essential to ensure the sustainability of the hydrogen economy.

- **Standards and certifications:** apart from the normalization of "low-carbon" hydrogen types (see the focus above), international standards for the molecule and its derived products need to be established. Such standards should also cover **safety issues** related to hydrogen and ammonia handling, as well as **purity levels** since various end-users do not require the same purity. For example, heating processes can perform with a 95% purity hydrogen, whereas fuel cells need a much higher levels.

- **Need for specific trainings and general hydrogen acknowledgement :** new hydrogen-related abilities and requirements are expected to appear within the next decades. Thus, equipment manufacturers, operational agents and project managers will need specific trainings to acquire such skills. The hydrogen safety culture must evolve to allow the development of the sector, covering both mobile and stationary applications. Sectoral guides will be required, especially for hydrogen charging stations as each new application involves specific features. The need for training is increasingly emphasised as public organisations embrace the subject: the *France Hydrogène* association has recently published a report highlighting the professions and certifications to be developed[2].

Risk and security management **FOCUS**

Safety is one of the major issues of the hydrogen industry development, since a major accident could dramatically slow down the development of the sector. The main risks are linked to the **emergence of new applications** and end users who are not familiar with the risks linked to handling hydrogen.
Most risks occur in the storage and production steps: geological storage in particular is still poorly understood and requires specific research work to be conducted. On the other hand, the risks associated with H_2 transport in pipelines (transport and distribution) are better understood. The question arises, however, whether H_2 is mixed into the existing natural gas network.
Although small-scale projects are globally mastered, the **scaling up of hydrogen projects** and the development of Gigafactories will increase the associated risks. Safety must be considered throughout the life cycle of the proposed projects: construction, installation, and maintenance, bearing in mind that safety cultures are not the same in industrial environments as in public environments.

Sources: [1] Yélé Consulting, 2021; [2] France Hydrogène, 2021

Certified safety training schemes related to the deployment of hydrogen projects in urban environments should also be developed since the various current demonstrators do not provide mature feedback on these issues. Setting up a common database to centralize all the data on the subject and developing this specific knowledge within the H_2 sector is critical for the future of the industry.

- **The need for clearer funding schemes from the EU and member countries:** several funding schemes are being deployed by the European Union and member countries to support hydrogen projects and decarbonisation initiatives. However, the specificities and eligibility criteria of each mechanism (technology readiness level, eligible costs between CAPEX and OPEX, hydrogen applications, etc.) are not well known yet by the different companies and private investors positioned over the hydrogen value chain. Such actors need to be supported to dispose of a clear understanding of these schemes and identify new business development opportunities related to clean hydrogen projects.

- **Further integration of hydrogen associations and organizations:** associations and organsations are key enablers of the hydrogen economy development, as multiple actors are still figuring out the whereabouts of hydrogen and its diverse applications. Europe is empowered by multiple agencies such as FCH JU and Hydrogen Europe, as well as national associations. These agencies play a critical role in hydrogen development on the continent as they act as bridges between the European Commission and the public and private actors interested in hydrogen development on the European continent. Furthermore, the EIB (European Investment Bank)[1] is active within the hydrogen[1] ecosystem as it is the institution that can help companies to get investments through Horizon Europe, thanks to its European Investment Advisory Hub.

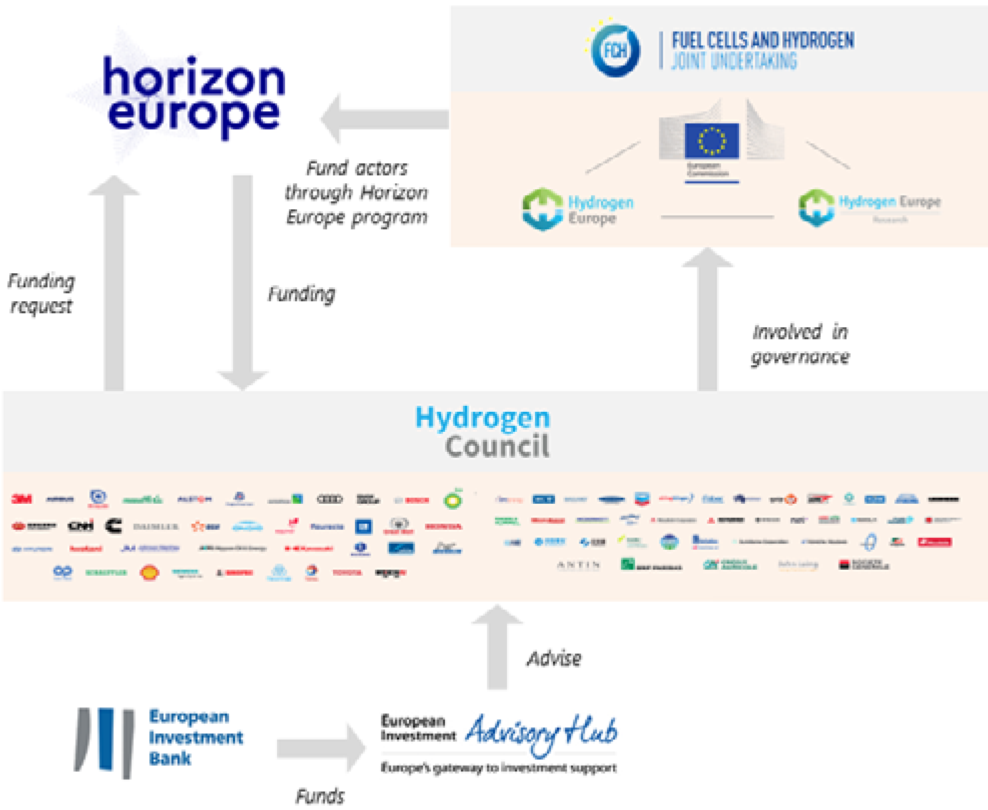

Fig. 24. The EU hydrogen ecosystem
(Source: Yélé Consulting)

Source: [1] *European Commission, 2015*

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SUGGESTED CITATION

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ANNEX: DETAILS OF THE ANALYSED MODEL AND SCENARIOS

In addition to the three main scenarios of the model (laggard, moderate and leadership scenarios[1]), two specific scenarios have been built and studied within the framework of this study:

- **Moderate scenario with increased hydrogen consumption:** the European energy system remains very similar to the moderate scenario. The shares of hydrogen for transport sector are increased to model a growing demand between 2020 and 2050.
- **Moderate scenario with increased low-carbon hydrogen production:** for this scenario, in addition to renewable hydrogen, the molecule can be produced through Steam Methane Reforming process (SMR) with the possibility of using carbon capture, transport and storage (CCTS), in order to analyse the competitivity between renewable hydrogen and low-carbon hydrogen.

The parameters of the main scenarios are available in the annex of the 100% Renewable Europe report from SolarPower Europe and LUT.

	2020	2025	2030	2035	2040	2045	2050	Units
Carbon pricing in all scenarios	28	52	61	68	75	100	150	€/tCO_2

Table 1 : Carbon pricing in all scenarios

MODERATE SCENARIO WITH INCREASED LOW-CARBON HYDROGEN PRODUCTION

This scenario is based on the reference moderate scenario. The model was modified to consider the production of low-carbon hydrogen by SMR+CCTS units. In order to steer the hydrogen market development during the transition, the scenario predefined minimum shares for renewable hydrogen in total hydrogen production (see figure 25) and minimum share of low-carbon hydrogen in the hydrogen production using SMR process (see figure 26).

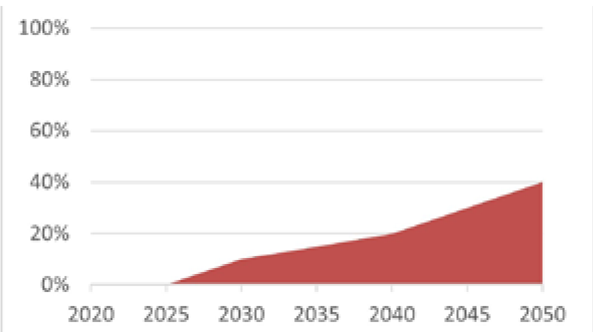


Fig. 25. Minimum shares of renewable hydrogen in the production mix

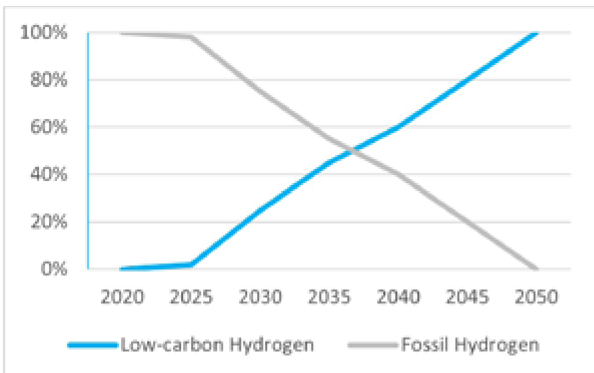


Fig. 26. Percentages of low-carbon and fossil hydrogen for the hydrogen produced by Steam Methane Reforming

Source: [1] LUT University and SolarPower Europe, 2020

	Parameters	2020	2025	2030	2035	2040	2045	2050	Units
CO_2 transport and storage (CO_2-TS))	CAPEX	N/A	0	0	0	0	0	0	€/kW
	OPEX fix	N/A	0	0	0	0	0	0	€/kW
	OPEX var	N/A	54	45	40	36	33	30	€/tCO_2
	Lifetime	N/A	30	30	30	30	30	30	years

Table 2: Parameters values of the Steam Methane Reforming process

	Parameters	2020	2025	2030	2035	2040	2045	2050	Units
SMR + CC	CAPEX	N/A	1221,6	1018	925	832	809	785	€/kW
	OPEX fix	N/A	46,44	38,7	35,2	31,6	30,7	29,8	€/kW
	Lifetime	N/A	30	30	30	30	30	30	years
	Efficiency methane	N/A	69%	69%	69%	69%	69%	69%	%
	Efficiency CO_2 capture	N/A	90%	90%	90%	90%	90%	90%	%

Table 3: Parameters values of the Steam Methane Reforming + Carbon Capture process

	Parameters	2020	2025	2030	2035	2040	2045	2050	Units
CO_2 transport and storage (CO_2-TS))	CAPEX	N/A	0	0	0	0	0	0	€/kW
	OPEX fix	N/A	0	0	0	0	0	0	€/kW
	OPEX var	N/A	54	45	40	36	33	30	€/tCO_2
	Lifetime	N/A	30	30	30	30	30	30	years

Table 4: Parameters values of the CO2 transport and storage

MODERATE SCENARIO WITH INCREASED HYDROGEN CONSUMPTION

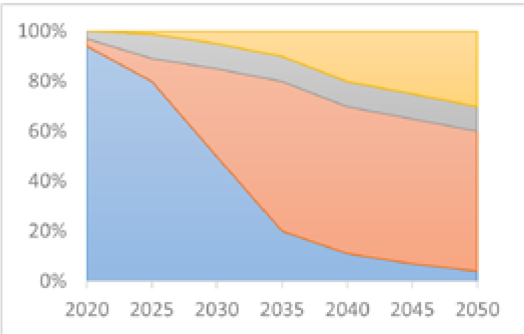
Although the development of hydrogen road transport seems unlikely, assumptions were made to justify the push for hydrogen mobility in the Moderate scenario with increased hydrogen consumption.

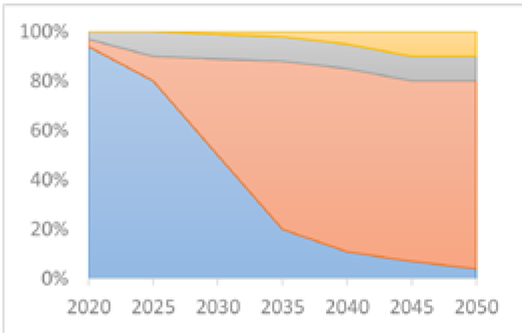
Sales shares of different vehicle types by fuel type for the moderate scenario with increased hydrogen consumption

Sales shares of different vehicle types by fuel type for the moderate scenario

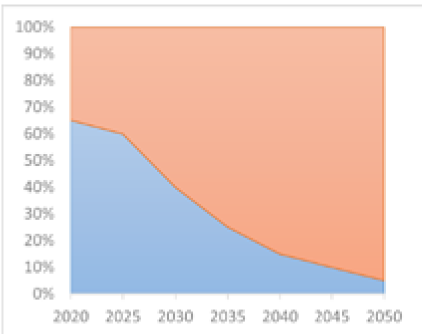
ICE BEV PHEV FCEV

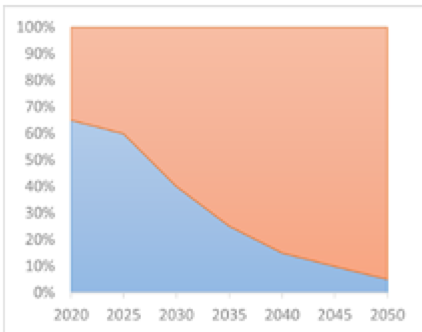
ROAD - PASSENGER – Light duty vehicles



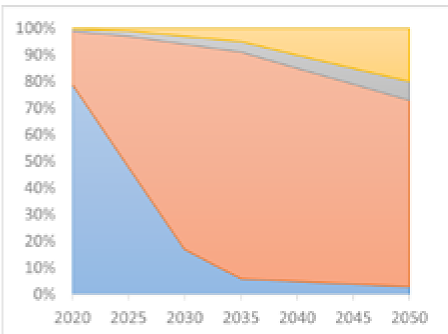


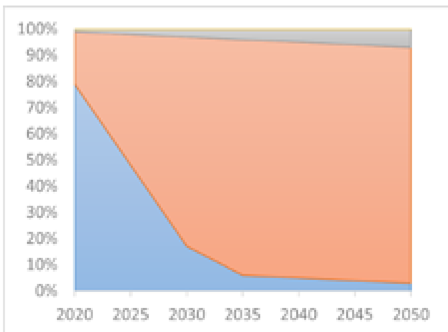
ROAD - PASSENGER – 2/3 wheels



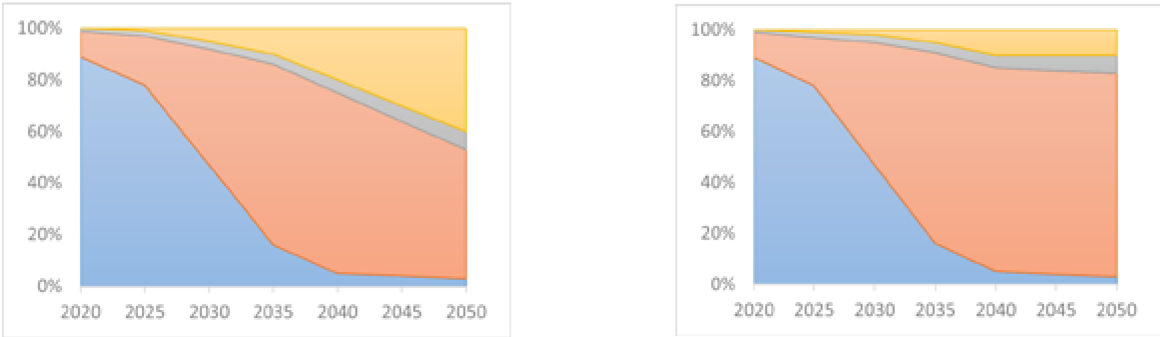


ROAD - PASSENGER - Bus





ROAD - FREIGHT – Medium duty vehicles



ROAD - FREIGHT – Heavy duty vehicles

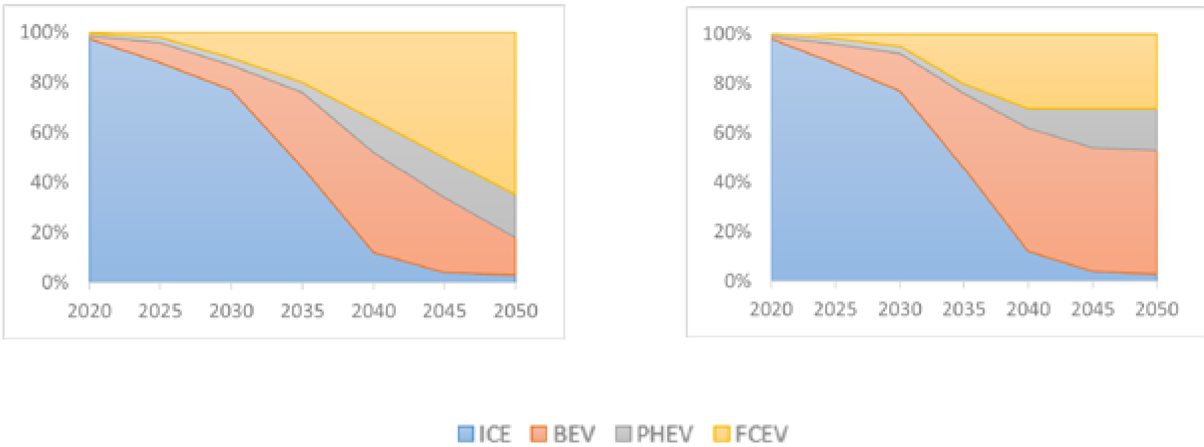


Fig. 27. Comparison of sales shares of different vehicle types by fuel type

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