Review

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Hydrogen: Prospects and Criticalities for Future Development and Analysis of Present EU and National Regulation

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Abstract: Hydrogen is in the spotlight in the energy world, and it will remain so for the next years. In Europe, the necessity to integrate ever growing amounts of Renewable Energy Sources (RES) in order to implement the ambitious European decarbonization policy (package Fit-for-55) and to preserve the security of energy supply (package Repower-EU) are feeding the interest in hydrogen. The paper will provide a thorough analysis of prospects and criticalities for the development of hydrogen both as a carrier and as a feedstock and, in definitive, as a key element for the implementation of the European decarbonization policies. First, the present regulatory framework will be highlighted, taking European Union as a main reference since it has presently one of the most advanced hydrogen legislations in the world. Then, both hydrogen offer (technologies and) and demand (both as a feedstock and as an energy carrier) will be dealt with in detail. Two additional sections will take care to illustrate, respectively, the interactions between hydrogen and the electricity grid and the issues related to the creation of a liquid hydrogen market. Finally, a conclusion section will wrap up and summarize the most urgent issues to be tackled to create a well-functioning hydrogen economy.

Keywords: Hydrogen; decarbonization; renewable energy sources; energy policy; carrier; feedstock

1. Introduction

In Europe, the evident signs of climate change that have characterized the last years have stressed even more the need for implementing a global decarbonization policy. Stringent goals have been established by national and trans-national policies, which call for replacing fossil fuels with Renewable Energy Sources (RES) for electric generation. In parallel, a strong reduction in the usage of fossil fuels is requested also to the industry and transport sector. In most cases, this implies a partial or complete electrification of the processes, which puts even more the accent on the need to develop a transition from fossil fuels to RES to generate electricity. However, RES generation is mostly characterized by an intermittent regime, which makes a high percentage of RES difficult to manage in the electric system, typically characterized by a low level of flexibility and by the necessity to match load with generation at each instant. In this framework, the deployment of new flexible resources (storage units and flexible loads) proves strategic to foster a higher penetration of RES in the electricity system, thus increasing the potential for the implementation of the decarbonization policies.

In this framework, hydrogen seems to have optimality characteristics which make it a very good allied of decarbonization policies.

Different hydrogen production processes entail the generation of very different amounts of CO_2, giving rise to the well-known color-code table shown in Figure 1.

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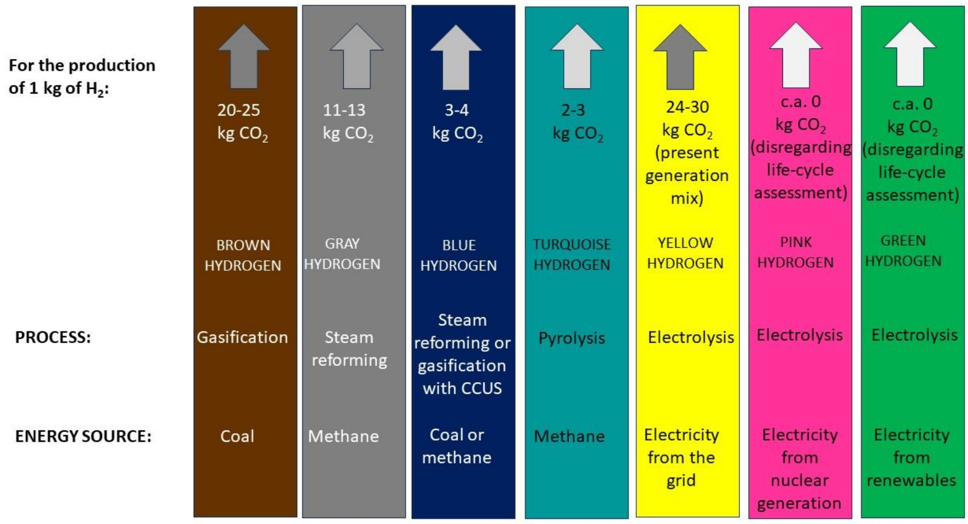

Figure 1. CO_2 generation for different hydrogen production technologies (CCUS = Carbon Capture Use and Storage).

Hydrogen can be employed both as a feedstock (to directly feed industrial processes) and as an energy vector (especially for the processes that cannot be easily electrified and in the transport sector).

As a feedstock, hydrogen is already used in some chemical processes (e.g. refineries), which presently produce it locally, often utilizing a methane reforming process. This process is not decarbonized and should be replaced by green or low carbon methodologies (water electrolysis, but also pyrolysis), In addition, other sectors, which are presently considered as "hard-to-abate" because the transition to decarbonized processes is deemed more complex to reach or requires important investments, should experiment new methodologies and analyze ways to support private investment by means of incentivization policies in order to make the new technologies more appealing for investors and favorize a swift transformation of the sector. An important example is constituted by the steel industry ([1,2]), maybe the most mature among the hard-to-abate sector, where there is already a mature technology (direct reduction) which can be employed to decarbonize the sector. Such technology can use methane or hydrogen to feed the process.

As an energy vector, hydrogen can be used to feed heating processes in several industry sectors which cannot be easily electrified (e.g. glass and cement sectors) and most notably in the transport sector. Minimizing the environmental footprint for the transport sector can significantly foster the achievement of an efficient and sustainable mobility. There is a need to conjugate a modernization of the transport sector with the attainment of challenging pollution and decarbonization objectives, in Europe as well as elsewhere in the world. In this sense, many Countries have undertaken specific legislative actions to encourage a different approach to mobility. In particular, the measures currently being adopted in Europe are aimed at ensuring a more sustainable mobility on urban and extra-urban public road transport and railway. The strategies being defined, at national and European level, aim at increasing independence and sustainability of the energy sector, and encourage private and public entities to adopt innovative solutions. In several countries the path to electrification for road service now seems to be firmly underway; in recent times, however, hydrogen traction is having, yet still to a small extent, a relative success, proving as a non-negligible tile for future international decarbonized scenarios ([29]).

In summary, hydrogen constitutes an important element of the world energy policies of the next years. The present paper aims at providing a review of present prospects and issues of hydrogen. Section 2 will be dedicated to outline the evolution of the regulation framework for hydrogen in the last years. In doing that, the European perspective will be adopted, being the European Union (EU) one of the most advanced "labs" in which the new regulation is elaborated and experimented. First the EU regulation will be introduced, then a few interesting differences in the legislation adopted by different EU countries will be highlighted. Sections 3 and 4 will provide details on the different potential usages of hydrogen, respectively as a feedstock and as a vector, to compose an overall picture of hydrogen demand in the medium and long period. Section 5 will introduce the main issues regarding the usage of hydrogen for storage in the electric grids and the topics related to the possible synergies between hydrogen and the electricity vector. Section 6 will analyze hydrogen supply and the technologies that can be used to produce it, which constitute the side of hydrogen offer. Section 7 will see hydrogen as a commodity and analyze the potential issues tied with the creation of a future hydrogen market. Section 8 will make the point on the current state of the research and development on hydrogen. Finally, section 9 will wrap up all consideration formulated in the paper and provide a few attention points on critical issues to be tackled in the next future by the world regulators to foster the development of a healthy hydrogen economy.

2. The EU Policy on Hydrogen and National Provisions

In the last years, the great interest towards hydrogen in Europe has been driven by two important pillars of the EU policy: decarbonization and security of supply, the former leading to the Fit-for-55 package ([3]) and the latter to the RepowerEU package ([4]). Both regulations have created a comprehensive framework to support the uptake of low-carbon and renewable hydrogen, with the aim of identifying ways to implement a decarbonization strategy in a cost-effective way and reduce dependence on fossil fuels.

However, to reconstruct the entire chain of policy provisions in Europe concerning hydrogen it is necessary to start with the EU hydrogen strategy ([5]), adopted in July 2020, so earlier than the Fit-for-55 and RepowerEU packages. Such document outlines an action plan aimed at achieving the following targets:

- support to the investments
- support for production and demand
- creation of a market and infrastructure for hydrogen
- boost to research and cooperation
- stimulation of an international cooperation.

The European Hydrogen Strategy has as its strategic objective to achieve the installation of at least 40 GW of electrolyzers for renewable hydrogen and to increase the production to up to 10 million tons of renewable hydrogen in the EU by 2030. The document proposes a twenty-point operational strategy, all of which were implemented by the first quarter of 2022 ([6]).

A further document ([7]) highlights the role of hydrogen in the EU strategy as an essential piece for the integration of the energy system and provides important indications about the opportunity to consider synergies between the various energy vectors - electricity, heat, cooling, gas, solid and liquid fuels.

The Fit-for-55 package, presented in July 2021 and including a set of provisions aimed at reducing net greenhouse gas emissions by at least 55% by 2030, provides, among others, a set of legislative proposals that translate the European hydrogen strategy into a concrete policy framework, including a proposal to set targets on the uptake of renewable hydrogen in industry and in transport by 2030.

Investment support is crucial for the long-term strategy and the Important Projects of Common European Interest on hydrogen ([10]) provide a substantial help in this respect. The first IPCEI package, called "IPCEI Hy2Tech"), includes 41 projects and was approved in July 2022. In September 2022, the Commission approved "IPCEI Hy2Use", comprising 37 projects, which complements the IPCEI Hy2Tech and supports the construction of hydrogen-related infrastructure and the development of innovative and more sustainable technologies for the integration of hydrogen in the industrial sector. These projects can be considered both as models and as precursors of future investments of increasing sizes.

Furthermore, the Clean Hydrogen Partnership ([11]), established in November 2021, provides important guidance on research and innovation for hydrogen.

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The RED III directive ([12]), adopted in 2023 by the European Parliament and Council, reiterates the centrality of hydrogen as a lever to enable the energy transition towards the objective of climate neutrality. Among its sub-targets, it is established that:

- as agreed by the Member States, 42% of hydrogen used in industry should come from renewable fuels of non-biological origin by 2030 and 60% by 2035,
- the combined share of advanced biofuels and biogas produced from feedstocks and renewable fuels of non-biological origin (RFNBO) in the energy supplied to the transport sector should be at least 1% in 2025 and 5.5% in 2030 (furthermore, by 2030 at least 1% must come from RFNBO),
- energy from RFNBO is counted towards Member States' renewable energy share and sectoral targets only if the reduction in greenhouse gas emissions resulting from the use of such fuels is at least 70%.

The two European regulations ReFuelEU Aviation ([13]) and FuelEU Maritime ([14]) establish, respectively, the conditions for sustainable air transport and the use of renewable and low-carbon fuels in maritime transport.

Still in the transport sector, the new Alternative Fuels Infrastructure regulation (AFIR, [15]) adopted in 2024 prescribes for each member state the drafting of a national strategic framework on hydrogen and recommends the following actions:

- all hydrogen refueling should be located either on the Trans-European Transport network (TEN-T) road network, including the most important connections between the main cities and urban nodes (i.e. an urban area where there is TEN-T network infrastructures, such as ports, including passenger terminals, airports, railway stations, logistics platforms and freight terminals, both within and surrounding the urban area), or within a road distance of 10 km from the nearest exit of a TEN-T road,
- all hydrogen refueling stations should be in urban nodes,
- for urban hubs, public authorities should evaluate the possibility of establishing hydrogen refueling stations within intermodal hubs (i.e. logistics platform specialized in combined transport) and could also supply hydrogen to other modes of transport, such as rail and internal navigation,
- to this end, member states shall ensure that, by 31 December 2030, publicly accessible hydrogen refueling stations are installed along the TEN-T core network at a maximum distance of 200 km from each other, designed for a minimum cumulative capacity of 1 ton per day and equipped with at least one 700 bar distributor and in each urban node.

Two delegated acts, formally adopted on 20 June 2023, provide further precision on what has to be considered as renewable hydrogen.

The first delegated act ([16]) defines the conditions under which hydrogen, hydrogen-based fuels or other energy carriers can be considered as RFNBO. It includes two types of criteria to ensure that hydrogen is renewable:

- The additionality requirement - The idea of additionality is to ensure that the increase in hydrogen production goes hand in hand with the increase in renewable electricity generation. To this end, the rules require hydrogen producers to stipulate power purchase agreements (PPAs) only with new and not already supported renewable electricity generation capacity.
- The temporal and geographical correlation criteria - These criteria ensure that hydrogen is produced only when and where renewable electricity is available. The criteria aim to prevent the demand for renewable electricity used for hydrogen production from incentivizing greater electricity production from fossil sources since this would have negative consequences on greenhouse gas emissions, demand for fossil fuels and related gas and electricity prices.

To support the rapid scale-up of electrolyzers, renewable hydrogen producers will have the option to sign long-term renewable power purchase agreements with existing plants (until 1 January 2028). Furthermore, it is permitted to combine renewable energy production with associated renewable hydrogen production on a monthly basis (until January 2030).

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The second delegated act ([17]) establishes a minimum threshold for the reduction of greenhouse gas (GHG) emissions from recycled carbon fuels and provides a methodology for calculating life cycle greenhouse gas emissions for RFNBO. Greenhouse gas emissions are considered during the entire life cycle of the fuels, including upstream emissions, emissions associated with electricity withdrawn from the grid, various processes and those associated with the transport of these fuels to the final consumer.

For the certification of renewable hydrogen, producers will be able to rely on an established third-party certification system, so-called voluntary schemes. Voluntary schemes and national certification schemes of EU countries help to ensure that biofuels, bioliquids and biomass fuels as well as renewable hydrogen and its derivatives (RFNBO), and recycled carbon fuels (RCF) are sustainably produced by verifying that they comply with the EU sustainability criteria, as well as the relevant methodologies for RFNBOs and RCF. Several schemes also take into account additional sustainability aspects such as soil, water, air protection and social criteria. For the certification process, an external auditor verifies the whole production chain from the origin of the raw material and energy to the fuel producer or trader. The Commission has been given the power to recognize voluntary and national systems for the certification of renewable hydrogen.

As regards the economic and financial aspects, it is important to consider the European hydrogen bank, established by the Commission in 2022, to guarantee investment security and commercial opportunities for the European and global production of renewable hydrogen. The European Hydrogen Bank is not intended to be a physical institution, but as a financial instrument, managed internally by the European Commission services. The Communication on the European Hydrogen Bank ([18]), published on 16 March 2023, describes in detail the concept, tasks and structure of the financial instrument. It is based on four pillars of action at EU level:

- domestic pillar, to support the expansion of the hydrogen production market within the European Economic Area and connect the supply of renewable hydrogen with demand,
- Hydrogen Bank Auctions: The first European-wide auction awarded almost €720 million to 7 renewable hydrogen projects across Europe under the Innovation Fund. Announced in April 2024, the winning projects were selected by the European Climate, Infrastructure and Environment Executive Agency (CINEA [19]) which assessed 132 bids submitted to the auction between November 2023 and February 2024 and ranked them into based on the offer price,
- international pillar, to promote a coordinated EU strategy on renewable hydrogen imports,
- transparency and coordination, to ensure transparency and coordination of information to support market and infrastructure development and improve coordination of existing support instruments of the EU and EU countries, including technical assistance and support to investments inside and outside the EU.

Finally, it is important to mention the Hydrogen Package, recently adopted by the Council (21. May 2024), consisting of a directive ([8]) and a regulation ([9]) establishing common internal market rules for renewable and natural gases and hydrogen and reforming the existing EU gas legislation. The gas package sets out solid rules for the organization of the natural gas market and establishes a strong framework for the development of the future hydrogen market, including for dedicated hydrogen infrastructure. The development plans for the national networks will have to be based on joint scenarios for electricity, gas and hydrogen and be aligned with the goals of the Fit-for-55 package and the EU Ten-Year-Network Development Plan (TYNDP, [22,23]). Gas TSOs will have to include information on infrastructures that can be dismantled or converted to hydrogen and draw up specific development plans for the H_2 network. The hydrogen market will develop in two phases, before and after 2033. In the first, a simplified framework will be in force to give visibility to future rules, especially the separation of H_2 production from transport activities ("unbundling"). A new governance structure along the lines of the electricity and gas European Network Transmission System Operators (ENTSO-E [20] and ENTSOG [21]) will be established, called the European Network of Network Operators for Hydrogen (ENNOH). The setting of network tariffs for hydrogen will be the prerogative of national regulators, who will however have to consult the authorities of neighboring countries and the EU Agency for the Cooperation of Energy Regulators (ACER, [24]).

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Concessionary tariffs must encourage the development of hydrogen in coal-bearing and "carbon-intensive" regions, while domestic consumers (especially vulnerable and in energy poverty) will be protected from supply interruptions, also thanks to the obligation to establish suppliers of last resort. A certification system for renewable and low-emission gases is then established and a ban on signing purchase contracts lasting beyond 2049 for fossil gas without abatement systems is established. The Member States will be able to limit and, in some cases, prohibit requests for access to the gas network and to LNG terminals to volumes from Russia and Belarus, even if only after having probed and taken into consideration any concerns from other European countries regarding the security of supplies. Finally, the platform for demand aggregation was made structural.

After explaining the overall EU regulatory context, we outline the Italian regulatory context as an example of EU Countries and provide an overview of the regulation provisions of other key European countries.

The guidelines for the Italian hydrogen strategy ([25]) issued at the end of 2020, have preliminarily identified a potential hydrogen demand for Italy of around 700 thousand tons per year by 2030, hence the need to install around 5 GW of electrolysis power activating investments of 5-7 billion euros.

The current proposal to update the 2023 National Integrated Climate and Energy Plan (PNIEC, [26]) revises the objective of the guidelines to 250 thousand tons per year by 2030. It is estimated that at least 80% of the aforementioned demand will be produced on the national territory, the remaining share will be imported. Assuming a load factor of the electrolyzers of 40%, an (electrical) capacity of approximately 3 GW of electrolyzers would therefore be required.

The National Recovery and Resilience Plan (PNRR, [27]) envisages various lines of action aimed at facilitating the development of hydrogen. Particularly significant are:

- two reforms concerning the administrative simplification and reduction of regulatory obstacles to the diffusion of hydrogen, aimed at defining a legal framework to promote hydrogen as a source of renewable energy, and fiscal measures to incentivize production and use of hydrogen.
- two investments for the production and use of hydrogen on two areas: hydrogen production in disused industrial areas (hydrogen valleys) and use of hydrogen in hard-to-abate sectors.

Finally, it is important to mention the recent public consultation (18 January 2024, [28]): "regulation of tariff incentives for the production of gaseous fuels from renewable sources referred to in article 11, paragraph 2 of the legislative decree of 8 November 2021, n.199." The most significant element of this consultation was the proposal to establish an operating incentive to accelerate the production of hydrogen from renewable sources aimed to be used in the transport sector and in industrial hard-to-abate sectors. The incentive is calculated with the following formula:

$$I = P_{agg} - P_{rif} - V_{GO/ETS} - R + O \quad (1)$$

where:

- I is the incentive due (expressed in €/kg of hydrogen)
- P_{agg} is the award price (strike price)
- P_{rif} is the price of the counterfactual fuel replaced (reference tariff)
- $V_{GO/ETS}$ is the value of the GOs and the ETS
- R is a reduction term applied in the case other incentives are received
- O is the value of the system charges.

The award price P_{agg} is defined following a competitive procedure (downward) and must be updated taking into account inflation and a revaluation based on the indexation to a benchmark price of electricity (this is to take into account the fact that the electricity used as raw material for the production of hydrogen represents a cost item that significantly affects the total cost of the hydrogen produced).

The reference price P_{rif} is determined on the basis of the fuel that is replaced by green hydrogen (called “counterfactual” fuel):

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- natural gas when hydrogen is used in the industrial sector. In this case the reference price is the average price of natural gas, expressed in €/smc, weighted by quantities, recorded on the day-ahead natural gas market and on the intraday natural gas market in the month of collection,
- diesel, when hydrogen is used in the transport sector to replace it. In this case the reference price is the price, expressed in €/liter, published monthly by the Fuel Observatory on the institutional website of the Ministry,
- gray hydrogen, when hydrogen (renewable or biohydrogen) is used in industry sectors that use hydrogen as a raw material in processes. In this case the reference price is indexed to the methane average price of the previous month in the virtual hub representing the place of exchange and sale of natural gas on the national network taking into account a typical efficiency of the thermochemical processes for the production of gray hydrogen.

Many EU Countries as well as other ones in the world have already elaborated national strategy documents on hydrogen. All these documents uniformly agree in admitting that substantial efforts are required to fully exploit the potential of hydrogen. The main present challenges include reducing production costs and increasing the availability of low-carbon hydrogen. To this end, there is a clear necessity to develop adequate infrastructures for hydrogen production, storage, transportation, and distribution through significant investments in facilities for its production by electrolysis, transportation systems, and distribution infrastructure to integrate hydrogen into the existing energy networks.

Table 1. Summary of the driving factors of European national strategies.

European Union [115,116]	Decarbonization of large shares of EU consumption using Hydrogen as vector for renewable energy storage and transport, ensuring back up for seasonal variations and connecting production locations to more distant demand centers. Replace fossil fuels in some carbon intensive industrial processes, such as in the steel or chemical sectors, lowering greenhouse gas emissions and further strengthening global competitiveness for those industries. Solutions for hard-to-abate parts of the transport system, in addition to what can be achieved through electrification and other renewable and low-carbon fuels.
France [117]	Environmental issues: hydrogen provides many solutions for decarbonizing industry and transport. Energy security issues: to reduce dependence on hydrocarbon imports. Challenges of technological independence: to enhance the strengths in global competition.
Germany [118]	Accelerated transition to a sustainable energy economy. Reduce greenhouse gas emissions by 80 to 95% by 2050 compared to 1990 levels.
The Netherlands [119]	H_2 crucial to the energy transition. Hydrogen specifically has the added benefit of contributing to better air quality. The rapid development of hydrogen will be a top priority for industry. A portion of German demand will have to be met through imports through the Netherlands.
Spain [120]	Hydrogen as main asset for Spain to become one of the European powers in renewable generation. The deployment of green hydrogen will encourage the development of innovative industrial value chains, generating employment and economic activity, contributing to the reactivation of a green economy with high added value. Accelerating renewable deployment, with positive effects on electricity prices and on industrial competitiveness. Development of smart grids and storage of renewable energy on a large scale and on a seasonal basis, providing flexibility to the system. Potential of renewable hydrogen to favor the decarbonization of isolated energy systems, with special attention to islands (highly dependent on air and sea transport).

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	Renewable hydrogen will be promoted to help prevent rural depopulation and achieve the demographic challenge objectives
Norway [121]	The government pursues a broad set of policies aimed at zero emission solutions in the transport sector. This also includes hydrogen.
United Kingdom [122]	Electricity pathway, Hydrogen pathway: 2050 hydrogen would provide a majority of heating for heating homes (62%) and commercial and public buildings (56%), power all cars and vans, and play a significant role in firing industrial processes. Emissions removal pathway. The transport sector was responsible for 24% of UK carbon emissions in 2014. The UK government has set a target for all new cars and vans to be zero-emission by 2040.

Table 2. Summary of the main tasks of European national strategies.

European Union	EU industry is rising to the challenge and has developed an ambitious plan to reach 2x40 GW of electrolysers by 2030. Generating 2,250 TWh of hydrogen within Europe by 2050 (approximately 24% of final energy demand). Decarbonise various sectors, especially the gas grid through blending and limited conversion to 100% hydrogen. Transportation through adoption of fuel cells in vehicles and shipping and synthetic fuel in aviation. Use in industry as a substitute for natural gas for high-grade process heat and as a feedstock in processes, either directly or with CO2 as a synfuel or electrofuel.
France	Strategy based on large consultation of stakeholders in order to: Accelerate the ecological transition and create a dedicated industrial sector, both domestic on a European scale Install enough electrolysers to make a significant contribution to the decarbonization of the economy (objective 6.5GW) Develop clean mobility, in particular for heavy vehicles: save more than 6 Mt of CO2 by 2030. Build industrial sector that creates jobs and guarantees technological leadership: generate between 50,000 and 150,000 direct and indirect jobs. Hydrogen production by electrolysis for industry, in mobility as a complement to battery vehicles, and to assist the stabilization of energy networks.
Germany	By 2030: Hydrogen demand is set to experience an initial increase – especially in the industrial sector (chemicals, petrochemicals, steel) and, to a lesser extent, in the transport sector). The demand in industry will rise by 10 TWh. Growing demand is expected to come from fuel-cell-driven electric vehicles. Other consumers (e.g. parts of the heating sector, in the long term) might follow. By 2050: The forecast consumption of electricity-based energy sources will be between 110 TWh - and roughly 380 TWh. Alongside the industrial and transport sectors, long-term demand will also arise in the transformation sector. Focus on close to commercial and on sectors hard to be decarbonized. Existing technologies will be insufficient; innovative technological solutions will be required. Strategy: speed up rollout of H2 technologies in Germany, encouraging other countries to adopt H2 by example. TIMING IS IMPORTANT: to avoid misallocated investments transformation process must be oriented to the demand expected in view of the 2050 decarbonization
The Netherlands	The government must meet the necessary preconditions, while businesses and knowledge institutions must start investing in scalable applications and innovation. Key concepts are upscaling, cost reduction (in an international context) and innovation.

	Presenting an ambitious policy agenda and taking the essential steps needed to realize the infrastructure and other framework conditions, the government wishes to send a clear signal. By national strategy the government underlines the unique starting position of the Netherlands. Hydrogen imports will also take up a key role as a global market begins to emerge. Alignment with the decisions and developments in the regions of our Northwest European energy market.
Spain	Potential of renewable hydrogen to decarbonise sectors or processes with greater decarbonization complexity, such as air transport or industrial processes that require high temperatures, power generation. Green hydrogen key to achieve climate neutrality and a 100% renewable electricity system by 2050. The renewable hydrogen will activate the development of the value chains. The Roadmap identifies this energy vector as a key sustainable solution for the decarbonization of the economy and the development of industrial value chains and RD&I, Role of hydrogen in the next three decades will allow Spain to lead a country project towards a decarbonized economy, fostering the innovative value chain, the applied knowledge of the industry, the development of pilot projects throughout the national territory and support for transition. This document is aligned with the Annual Sustainable Growth Strategy for 2021 published by the European Commission.
Norway	Hydrogen is currently not competitive in many of the areas of application that could be of interest. Energy losses generated by producing hydrogen and the cost of storing it make the utilization of clean hydrogen less profitable compared with fossil energy sources or other low and zero emission solution. More stringent emissions trading market, combined with the increase in the CO2 tax announced by the government, will make emission-intensive solutions more expensive. Technologies are not yet mature: Technology development and innovation in a value chain perspective could assist in drawing on potential synergies between industries: developing and demonstrating energy-efficient and cost-efficient methods and value chains for the production, transport, storage and use of clean hydrogen. Uncertainties regarding the opportunities for H2 in Norway: the technology for several of these applications is at an early stage. Several of the applications being considered in other countries are of little relevance to Norway. Open issues: In addition to the price of input factors such as electricity or gas, factors such as distance from producer to consumer, the need for storage, demand, and the costs and energy losses associated with chemical conversion matter. For hydrogen used in vehicles/vessels, it is important to emphasize that the combined weight of fuel, tanker, propulsion system and space required will also be significant. Pilots: there are few projects operating with end-user experience in the use of hydrogen. PILOT-E: 71MNOK complete supply chain for H2
United Kingdom	Blue Hydrogen. This type of hydrogen is preferred cause: Total hydrogen production would reach approximately 700 TWh in 2050. The main form of production would be steam methane reforming with carbon capture, usage and storage. A key aim of the Hydrogen Supply Programme is to overcome the cost differential between low carbon hydrogen and natural gas. SMR (4 x 256 MW capacity) was chosen as it is a proven technology, has a relatively smaller footprint, and can be integrated into the existing natural gas supply chain. As this approach involves the production of carbon emissions, carbon capture technology would be included to capture 90% of emissions for subsequent sequestration (1.5 million tons per annum). Green Hydrogen. Production using electrolysis was not considered practical due to various factors:

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	limited availability of curtailed electricity. cost of existing bulk grid electricity leading to "expensive" hydrogen production cost. substantial land requirements for dedicated renewable energy supply (i.e. wind) and electrolysers (400 x 2.6 MW units). additional storage requirements to accommodate variability of wind power and additional costs of associated electrical infrastructure. Assuming a bulk electricity cost of 6 p/kWh, the cost of producing hydrogen at the electrolyzer was estimated to be 10 p/kWh, excluding transmission and storage costs.

Recent updates to national strategies highlight the imperative necessity to foster a significant growth in the hydrogen industry, emphasizing the need for increased investments and to intensify research and development efforts to enhance hydrogen production, storage, and utilization. This indicates that the international community increasingly recognizes hydrogen as a fundamental component of decarbonization strategies and the transition towards a low-carbon economy.

As already mentioned, primary focus of the national policies is on creating the right ecosystem to foster a substantial reduction of hydrogen production costs, with notable advancements observed, particularly in the production of green hydrogen from renewable sources. Furthermore, the expansion of dedicated hydrogen infrastructure underlines a growing commitment to establishing a robust logistical foundation to support the wider adoption of hydrogen. Investments in such infrastructure are crucial for ensuring availability and accessibility of clean hydrogen to the industry, to the transportation sector and to the energy sector.

Regarding future scenarios for the expansion of hydrogen utilization, the International Energy Agency document "Global Hydrogen Review" published in 2023 [123] provides a comprehensive overview of the current state of the hydrogen industry and global trends for the future. It underlines the importance of clear and supportive policies and regulations to facilitate the development of a hydrogen production industry. Financial incentives, environmental regulations and energy transition strategies are deemed critical factors in accelerating the adoption of clean hydrogen and promoting its large-scale use.

Globally, the number of low-emission hydrogen production projects is rapidly expanding. However, so far, a final investment decision has been taken only for 4% of this potential production. Nonetheless, this represents a doubling in absolute terms compared to the previous year (reaching nearly 2 million tons). Out of this total, 27 million tons are based on electrolysis and low-emission electricity, whereas 10 million tons rely on fossil fuels with carbon capture, utilization, and storage. Consequently, the international community regards hydrogen as a pivotal element in the transformation of the global energy system towards environmental sustainability and the achievement of the Sustainable Development Goals (SDGs). Nevertheless, it is also acknowledged that further technological advancements, targeted policies, and significant investments are also essential to fully unlock hydrogen's potential as part of the future energy mix.

3. Hydrogen as a Feedstock

Currently, approximately 95% of hydrogen is produced and utilized in refineries and the petrochemical industry, with the remaining 5% having various minor uses. Moreover, 99% of its utilization is as a feedstock, i.e. it is required in the chemical process itself. Presently, hydrogen is primarily produced and used in refineries through the Steam Methane Reforming (SMR) process or the gasification of heavy petroleum distillates (TAR) in Integrated Gasification Combined Cycle (IGCC) plants. Both processes use fossil fuels as raw materials and consequently release CO_2. For the SMR process, there are no significant impediments to the use of biomethane, which is a purified version of biogas, produced from the breakdown of organic matter, whereas the IGCC process faces substantial challenges in substituting TAR with biomass.

In refineries, hydrogen is mainly used to refine crude oil and upgrade heavier crude. The main hydrogen-consuming processes in refineries are hydrotreating and hydrocracking. Hydrotreating is used to remove impurities, particularly sulfur (often simply referred to as desulfurization). This represents globally a significant share of refinery hydrogen use. Today, refineries remove about 70%

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of the sulfur naturally present in crude oils. Hydrocracking is a process that uses hydrogen to convert heavy residual oils into more valuable petroleum products.

Another significant hydrogen-consuming industrial sector is the production of ammonia. In the process developed in the early 1900s by Fritz Haber and later industrialized by Carl Bosch, nitrogen and hydrogen are reacted in a molar ratio of 3:1 to produce one mole of ammonia in three fixed-bed reactors in series. Ammonia is a toxic, colorless gas with a pungent, characteristic odor, but it has the advantage of being able to be condensed at -34 °C at atmospheric pressure or liquefied at room temperature at a pressure of around 8 atmospheres. 80% of produced ammonia is currently used in fertilizers production. The first passage to produce fertilizers is the production of urea, a key component of fertilizers. This process is based on the chemical reaction between ammonia and CO_2. Currently, the CO_2 used in the process, captured from the SMR process, is of fossil origin. Therefore, ammonia production results in a significant amount of CO_2 emissions, around 5 kg per kg of product (including the fertilizer application phase). If ammonia production for urea were, instead, produced from green hydrogen and CO_2 from biomass or biomethane, it would be possible to obtain fully green ammonia and fertilizers. In the petrochemical industry, hydrogen is used for methanol production, which is a base component for numerous chemical products. Methanol is currently obtained from SMR of natural gas or the gasification of coal, followed by a catalytic process to produce synthesis gas (syngas). Additionally, hydrogen is used for the production of plastic products through hydrogenation. As with fertilizer production, methanol production could become green provided that the utilized hydrogen is generated from biomass or biomethane.

Another significant use of hydrogen as a feedstock is in direct reduction processes of metallurgical compounds. Specifically, in integrated steelmaking, hydrogen can be used as a reducing agent, replacing coal, and substituting the current blast furnace-based cycle with a combination of direct reduction and melting of pre-reduced iron. This option is present in all major steel industries worldwide. The transition involves an initial phase of installing a direct reduction process making use of natural gas, followed by a second phase in which natural gas is gradually replaced by hydrogen.

4. Hydrogen as an Energy Vector

The other important utilization of hydrogen is as an energy vector, i.e. to transfer energy, usually produced in some other form (e.g. electric energy), and stock it to feed some process to get mechanical work. This can be used for decarbonizing some "hard-to-abate" sectors like:

- steel production and processing,
- foundries (steel, cast iron, and non-ferrous metals),
- cement,
- glass,
- ceramics,
- paper,
- transport.

All decarbonization strategies for the above sectors agree on some common aspects:

- increasing energy efficiency, especially through the recovery of energy from thermal waste,
- electrification of the processes, particularly by exploiting availability of electricity from renewable sources,
- use of alternative fuels (from biomass and recycled materials) to replace fossil fuels,
- circular economy practices that reduce both raw material consumption and the amount of byproducts to be disposed, along with the associated emissions,
- carbon capture and sequestration,
- use of hydrogen-based technologies to replace materials and fossil fuels,
- sector analysis.

To replace fossil fuels with hydrogen in these high-temperature industrial processes, solutions must be found for a series of technological challenges that still exist due to the diversity and specific

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nature of the energy conversion devices (such as furnaces, kilns, boilers, and reactors) used in these sectors. The following challenges have already been the subject of studies, with some partially overcome and others in the process of being resolved:

- Hydrogen has a high flame speed compared to carbon-containing fuels and a non-luminous flame, making optical monitoring difficult. These challenges can be partially overcome by using hydrogen/ammonia mixtures, as ammonia burns at a much slower rate and with a visible flame, also helping to reduce nitrogen oxide emissions.[124–127].
- Hydrogen flames achieve relatively low heat transfer by radiation compared to other fuels, necessitating the introduction of other carbon-free fluids. In the cement industry, for instance, clinker dust is used in the fuel stream. It may be necessary to redesign current burners to handle any new additives introduced (e.g., to manage the abrasive properties of clinker dust) [128,129].
- Hydrogen causes corrosion and embrittlement when in contact with certain metals, requiring new coatings and other protective measures [130].
- Intermittent hydrogen sources might pose difficulties for high-temperature heat uses that perform continuous processes, necessitating stable and reliable hydrogen supplies [131,139].

These challenges highlight the complexity and specificity of integrating hydrogen into existing industrial processes, requiring extensive research and innovation to ensure feasible and cost-effective solutions.

The comparison of strategies across various sectors [132–137] indicates that the steel industry and the glass industry (particularly container glass) have the most significant opportunities for hydrogen utilization, with several projects already underway. Other sectors consider hydrogen among the options but have no significant ongoing projects, and face greater challenges.

The steel industry uses a significant amount of natural gas in the electric arc furnace for scrap melting (in the electric cycle scrap route), in reheating and treatment furnaces (in both integrated and scrap routes), and for reactor preheating. This natural gas can be replaced by hydrogen, utilizing hydrogen combustion technologies and mixtures of natural gas and hydrogen. The same solution can, in principle, be adopted for all thermal processes currently using natural gas or other fossil fuels, such as coal and fuel oil. This solution is already in the experimental phase in the glass sector. In other sectors, it is conceptually possible but lacks significant industrial projects.

Consumption for auxiliary services (for example: heating of work environments, transport systems within the plant, consumption for small processes, etc.) are difficult to replace by hydrogen and will be covered by the use of electricity or biofuels. It can be estimated that the fraction of natural gas that can be replaced with hydrogen will be approximately 76%. On the basis of some projects currently being tested, it is possible to hypothesize a significant reduction in gas consumption in heating furnaces. For example, some industry has already achieved the electrification of the rolling processes ranging from the semi-product of billet steel to the finished products. The billets are heated with an induction furnace instead of methane. New plants have been already realized with electric furnace steel works with a rolling mill connected directly to a direct continuous casting without the need for a heating furnace. For now, these are small-sized plants but in the future technological development may allow these processes to be applied to large-sized plants too.

Today, the foundry and nonferrous metals industry uses natural gas as its primary fuel. Hydrogen can realistically replace fossil fuels used for the core foundry business, metal smelting and metallurgical heat treatments. Instead, consumption for ancillary services will more likely be decarbonized with electricity-based solutions. The introduction of hydrogen mixed with natural gas in processes or parts of them represents one of the possibilities of greatest interest for the sector in reducing emissions. A progressive closure of dome furnaces, which use coke, for the production of cast iron castings, with technologies based on electricity, is expected. The realistically feasible actions for total decarbonization are the replacement of natural gas in gas ovens (in the production of cast iron and non-ferrous metals) and the replacement of ovens powered by fossil fuels (coke, methane) with electric ovens [140]. Currently the projects under development are oriented towards the replacement of natural gas with biomethane. The objective is to reduce natural gas consumption by 20-40% by 2025.

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The cement industry has a high temperature process however there are several solutions that can significantly contribute to decarbonization. On the basis of the most authoritative strategies developed by industry operators (e.g., Federbeton) [141], several measures are possible for decarbonizing the existing cement production process [142]. These include carbon capture and storage (CCS); use of alternative fuels such as secondary solid fuels (SSF); increasing the clinker-cement ratio; use of alternative substitution materials; extensive use of renewable electricity; energy efficiency improvements and utilization of hydrogen. A significant portion of the CO_2 emissions in the sector is caused by the production of clinker, a crucial component in cement production. Hydrogen can be used as a reducing agent in the raw mix, helping to reduce the amount of clinker required in cement production. This could contribute to a 50% reduction in CO2 emissions. Therefore, while hydrogen may play only a limited role in the cement sector, it is yet essential for achieving the overall reduction of CO_2 emissions, which account for approximately 3% of the total annual CO_2 emissions from the cement industry.

For the glass sector, it can be hypothesized, based on technological developments and that in the coming decades the current furnaces will necessarily be replaced, it is expected that only electricity will be used for small and medium-sized furnaces [143]. For large furnaces, which will represent around 30% of total glass production, hydrogen will still be necessary because the heat generated by the hot burnt gases allows for better diffusion of heat by convection necessary for the homogeneous distribution of process temperatures.

In the ceramic sector, the same considerations made for the glass sector apply small and medium-sized plants will move towards massive electrification of processes. In this sector, hydrogen will therefore be used for large ovens in synergy with electric heating. The use of hydrogen is necessary so that the heat generated by the hot burnt gases guarantees well-distributed and homogeneous heat transmission by convection in terms of process temperatures.

The paper industry does not require high process temperatures. Thermal consumption is represented by steam, which can be produced with electric heating or biofuels. In this sector, any use of hydrogen will depend above all on the availability and specific cost with a view to maintaining the cost competitiveness of paper products. This contribution is considered negligible for the moment.

Hydrogen combustion technologies are in an advanced stage of development. Burners for hydrogen and mixtures, capable of operating flexibly with any blend of natural gas and hydrogen, have been extensively tested. Many models are already on the market with industrially relevant power levels.

The technological feasibility of hydrogen combustion, whether pure or in mixtures, is considered as established. Potential challenges include the impact on product quality and possible negative effects on plants, with potentially higher material and maintenance costs. These aspects need to be thoroughly investigated through long-term tests on diverse products.

Another point concerns the safety aspects of the routine use of hydrogen. Hydrogen is already regularly used in several industrial sectors. For example, in the steel industry, processes and related plants using pure hydrogen are well established. Thus, there is already a culture of safety in the use of hydrogen. However, this culture must be extended to the routine application of hydrogen combustion systems and all transport, storage, and control systems for applications requiring much larger volumes.

These issues are well-known and are addressed in numerous national and international projects.[44] These projects see significant participation from industrial sectors, and early results demonstrate that the technological feasibility of hydrogen combustion to replace fossil fuels is not in question.

Ongoing projects have two main objectives:

- optimize solutions to be competitive with conventional solutions,
- assess the advantages and disadvantages of current and developing technological solutions to choose the most convenient [one based on production goals and decarbonization needs.

Hydrogen demand can be met either through direct production via electrolysis or by purchasing hydrogen distributed through a network. Both solutions are under development.

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Potential demand and forecast of electrolysis capacity availability are consistent, with electrolyzers capable of gigawatt-scale capacity. The bottleneck is the availability of electricity from renewable sources. The extensive application of hydrogen in these sectors requires at least doubling the current production of electricity from renewable sources. This increase will necessarily need to be realized mostly through the realization of new photovoltaic and wind fields.

Analyzing the technical feasibility of these projects requires studying and fine-tuning new solutions. This must be done through real case studies that allow the analysis of proposed solutions, measurement of benefits and costs, and identification of critical issues for the application of hydrogen combustion technologies. The analysis of the possible profitability for potential investors is also a key element and should be done in relationship with possible existing incentivization programmes foreseen by the national regulation.

Hydrogen in the form of ammonia could play an important role as a hydrogen carrier in storing energy from renewable sources and facilitating its transportation over long distances by sea or in dedicated pipelines. Australia is particularly active in this area, with several pilot plants for producing ammonia from renewable sources and various ongoing research projects. According to Japan's National Hydrogen Strategy [138] for replacing fossil fuels, the cost of importing blue ammonia from Australia is estimated to be less than $340 per ton of NH3, equivalent to approximately $2 per kg of H2.

In the transportation sector, in the future, hydrogen is foreseen to acquire a strategic role for mobility. However, the energy efficiency of hydrogen vehicles is, at least presently, quite low. The main application consists of using hydrogen in internal combustion engines (Hydrogen Internal Combustion Engine Vehicle, HICEV). This technology has reached the level of prototype, but not yet the commercialization phase, while the fuel cell technology (Fuel Cell Electric Vehicle, FCEV) isn't able to guarantee a sufficient level of efficiency ([29]).

With HICEV technology the vehicle engine is powered by the direct combustion of hydrogen, converting the chemical energy of hydrogen into mechanical energy. The advantage of this type of fuel compared to traditional fuels is the absence of carbon. By burning hydrogen, exhaust emissions such as carbon monoxide (CO), carbon dioxide (CO_2) and unburned hydrocarbons (HC) are avoided. However, the high-temperature combustion of hydrogen with air, in addition to water vapor, produces nitrogen oxides (NOx) which have harmful effects on the environment and human health ([30]) and contribute to the formation processes of photochemical smog ([31]). Hydrogen combustion engines cannot therefore be considered zero-emission; their exhaust emissions may require similar treatment to that of vehicles powered by traditional fuels ([29]).

In FCEV cars, hydrogen in the gaseous phase is stored in high-pressure tanks to be subsequently fed into a fuel cell. The fuel cell is a chemical-electrical converter that transforms the chemical energy of a fuel directly into electrical energy, without an intermediate combustion cycle. A single cell consists of two electrodes, separated by the electrolyte, in which an oxidation semi-reaction occurs at the anode, where hydrogen arrives, and a reduction one at the cathode, where air is sent. A direct electric current is generated, which through an inverter power an electric traction motor; the overall reaction is exothermic and produces water at the cathode.

One of the most common Fuel cell technologies is the so-called PEMFC (Proton Exchange Membrane Fuel Cell). In more detail in PEM cells (Figure 2), an electrolyte membrane is inserted between the cathode and the anode. A stream of hydrogen is supplied to the anode while oxygen (from the air) is introduced to the cathode. In the anode, the hydrogen molecules break down into protons and electrons, thanks to the electrochemical reaction activated by the catalyst (usually platinum) of the fuel cell. The polymer membrane allows protons to pass through, which thus migrate towards the cathode. Instead, the electrons are forced to travel through an external circuit to reach the cathode. In this way, the current developed by the fuel cell is generated, which supplies energy to the car's electric traction motor. The electrons recombine with the protons on the cathode side and then with the oxygen molecules to give rise to water and steam which is released to the exhaust.

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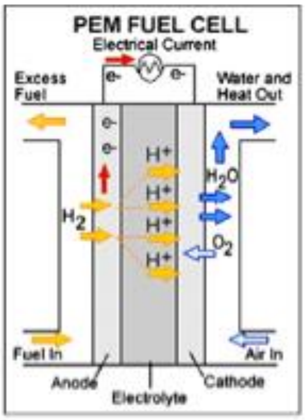


Figure 2. Diagram of a PEM fuel cell (source [32]).

In addition to the fuel cell, another essential component of the hydrogen car are the cylinders, in which hydrogen is stored in gaseous form at very high pressures (around 700 bar) which require the use of composite materials. Other components (Figure 3) are very similar to those of pure electric vehicles.

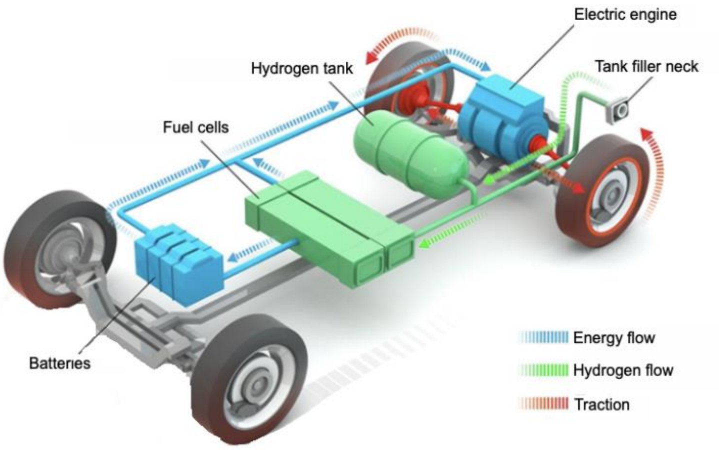
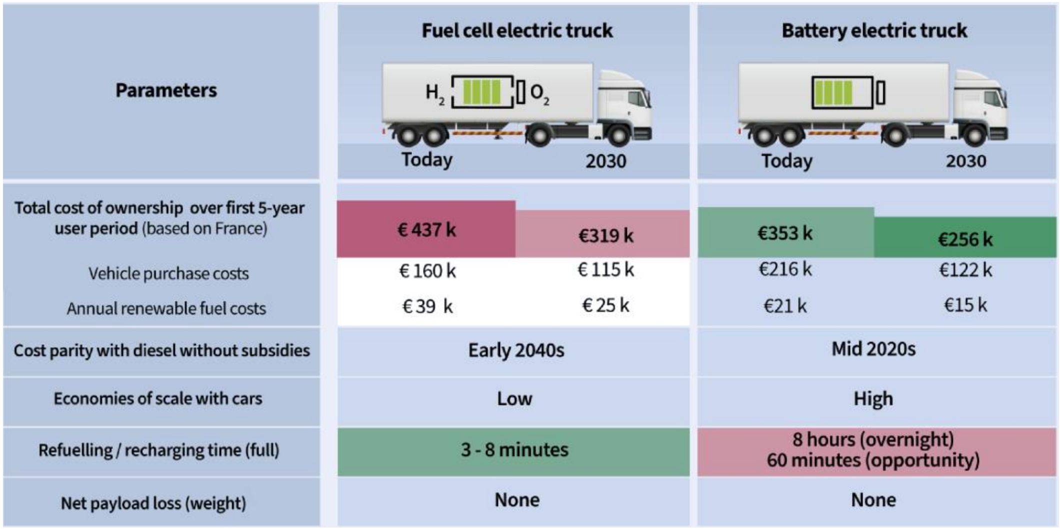


Figure 3. Main components of an FCEV car (source [33]).

High costs due to the constructive complexity of a hydrogen fueled vehicle and a current lack of sufficient development determine nowadays that hydrogen does not appear to be a preferable option for light vehicles, at least for the next decade and perhaps even beyond. In the light transport sector, decarbonization strategies are progressively converging towards electrification, by utilizing batteries and electric motors.

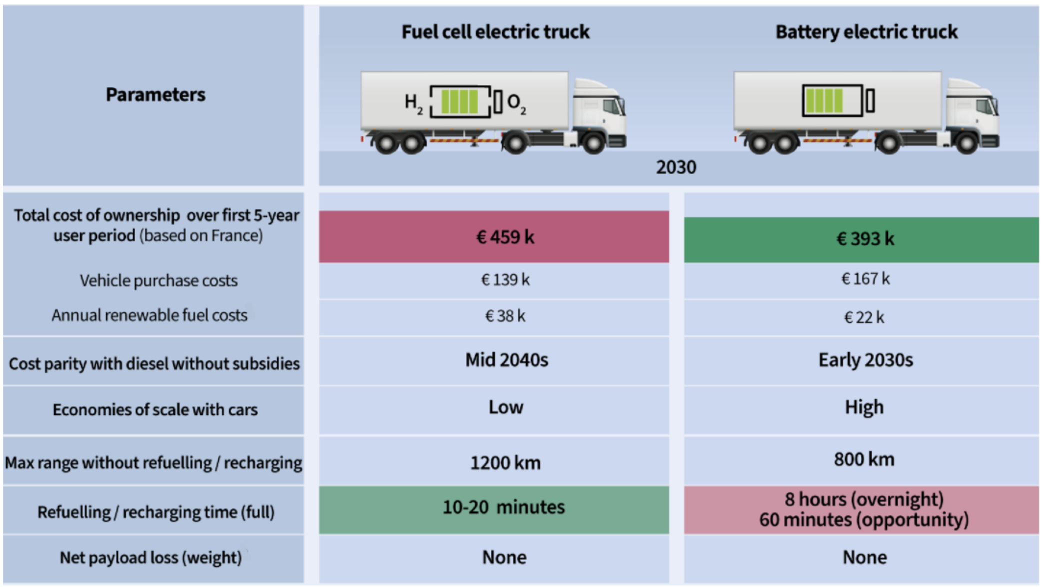
In terms of heavy road transport, despite the overall uncertain outlook, hydrogen is considered a possible solution. This solution also benefits of the fact that there is currently no interoperability agreement for electric heavy vehicles nor plans for high-power charging stations across European borders. Anyway, there are some criticalities due to high cost of vehicles, in particular in comparison with electric ones, and spread of refueling station, even more fundamental for heavy vehicles and long-distance autonomy.

About the first aspect many studies have delved deeper into the topic (like [34] for a typical tractor-trailer with a gross combined vehicle weight – GCVW - of 40t, a vehicle curb weight of 14t and a resulting maximum payload of 26t and an electric drivetrain with a combined rated power output of 350 kW) and determined the excessive total cost of ownership of a hydrogen truck, both for regional and long-distance delivery (Figures 4 and 5).



Parameters	Fuel cell electric truck – Today	Fuel cell electric truck – 2030	Battery electric truck – Today	Battery electric truck – 2030
Total cost of ownership over first 5-year user period (based on France)	€ 437 k	€319 k	€353 k	€256 k
Vehicle purchase costs	€ 160 k	€ 115 k	€216 k	€122 k
Annual renewable fuel costs	€ 39 k	€ 25 k	€21 k	€15 k
Cost parity with diesel without subsidies	Early 2040s		Mid 2020s	
Economies of scale with cars	Low		High	
Refuelling / recharging time (full)	3 - 8 minutes		8 hours (overnight) 60 minutes (opportunity)	
Net payload loss (weight)	None		None	

Figure 4. Hydrogen vs electric truck in regional delivery (source [34]).



Parameters	Fuel cell electric truck (2030)	Battery electric truck (2030)
Total cost of ownership over first 5-year user period (based on France)	€ 459 k	€ 393 k
Vehicle purchase costs	€ 139 k	€ 167 k
Annual renewable fuel costs	€ 38 k	€ 22 k
Cost parity with diesel without subsidies	Mid 2040s	Early 2030s
Economies of scale with cars	Low	High
Max range without refuelling / recharging	1200 km	800 km
Refuelling / recharging time (full)	10-20 minutes	8 hours (overnight) 60 minutes (opportunity)
Net payload loss (weight)	None	None

Figure 5. Hydrogen vs electric truck in long-distance delivery (source [34]).

About infrastructures, although there are virtuous efforts ([35–37]), the lack of refueling stations is evident. According to IEA ([38]), only at the end of 2020, 540 refueling stations were operational worldwide, mainly located in Japan (25%), followed by Germany (17%), China (16%) and the United States (12%). In summary economic and infrastructural factors are still currently holding back and making the possible development of the hydrogen heavy transport solution unfavorable.

Regarding local public transport, which will see a progressive replacement of the existing fleet, it is possible to expect a significant expansion in the next years, especially in local districts for production, distribution, and use of hydrogen (hydrogen valleys), where there will be availability of large quantities of hydrogen for use in FCEV buses, predictably at more competitive costs than current ones (e.g. [39]). As regards the bus sector, hydrogen fueling partly presents the same problem that occurs with methane-powered vehicles, where the autonomy, more than suitable for urban and suburban cycles, is however limited. The older fuel cell buses currently in circulation use from 5 to 8 cylinders containing a total of up to 600 liters of fuel, where 1 kg of hydrogen compressed at 350 bar is equivalent to approximately 4 liters if liquefied at -253 °C (at room temperature , however, the equivalence is approximately 42 l/kg) ([40]). Until 2020, for that capacity, the vehicles available on the

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market were able to offer an autonomy of approximately 350 ÷ 400 km while latest generation models reach 600 ÷ 700 km with 35 kg of refueling.

The greater energy density of the fuel compared to batteries makes fuel cell vehicles more suitable for applications over long distances, i.e. on extra-urban routes, a fact which, as will be seen later, is not currently contemplated in the national scenario. According to ([41]) by 2040, hydrogen fueling will represent 1.5% of truck sales, 3.9% of heavy goods vehicles and 6.5% of global annual sales of local public transport buses.

Hydrogen can contribute to reducing emissions in the transport sector, but only if the latter is developed at a sufficiently large scale to reduce costs (Figure 6, [42]).

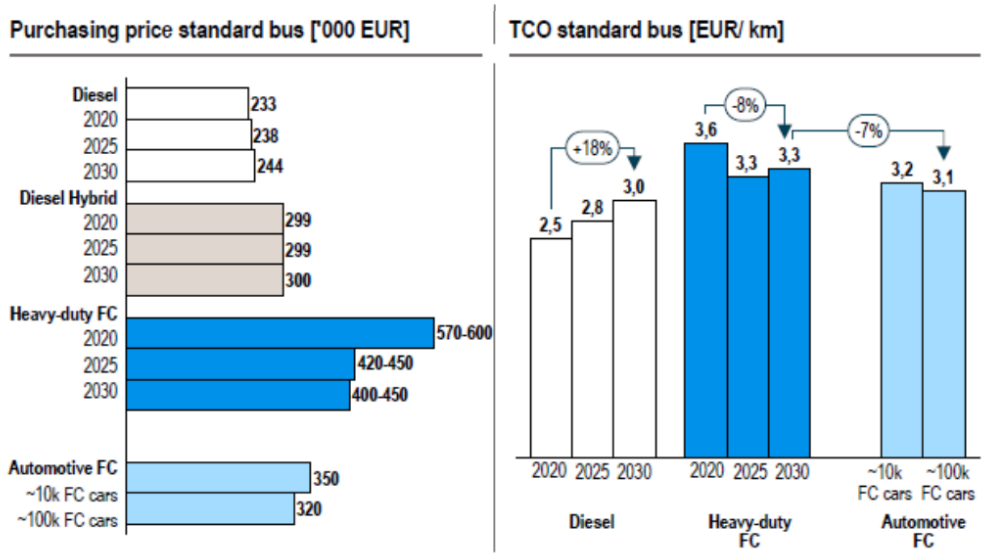

Figure 6. Costs evolution in decade 2020 - 2030 for different fuel buses in comparison with other vehicle types (source [44]).

Fuel cell buses offer good efficiency and operational flexibility ([45]) (**Table 3**). In terms of costs, it is expected that in the long-term fuel cell buses can be compared with other zero-emission propulsion systems: despite an undeniably higher cost.

Table 3. Performance comparison of different zero-emission bus concepts (elaboration on [45]).

Vehicle type	Autonomy	Operation flexibility	Refuel/ Recharging time	Passenger capacity
Electric overnight	+ / -	+ / -	-	-
Electric opportunity charging	+	- / +	+ / -	- / +
Trolleybus	+	-	+	+
Fuel cell	+	+	+	+

What concerns railway mobility, beyond the diffusion of native hydrogen trains, mainly limited due to very high costs (Figure 7), it includes some interesting proposals consider some experiences of retrofitting diesel locomotive to get fit for hydrogen fueling. First outcomes establish that retrofit costs are between 30 and 50% less than purchasing an equivalent native rotatable hydrogen power supply ([43]).

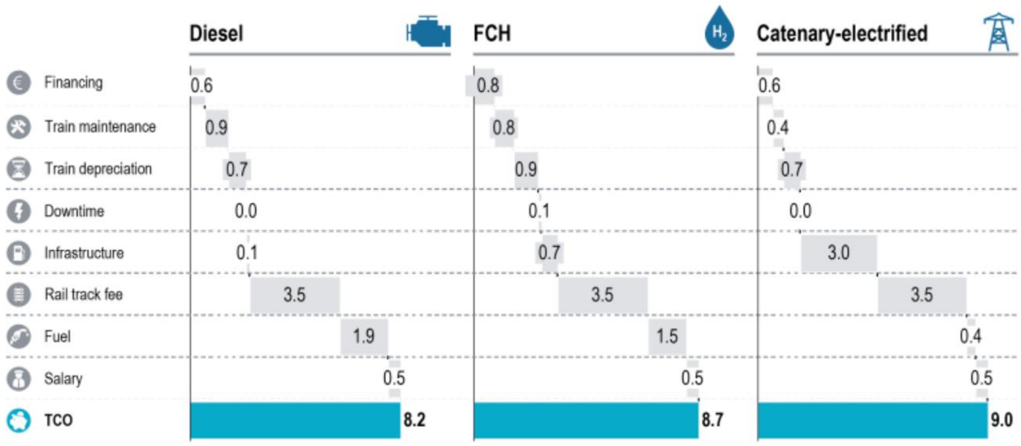

Figure 7. Cost TCO comparison (€/km) between diesel, hydrogen (FCH) and electric trains using electric catenary (source [44]).

Potentially interesting developments could occur in the maritime sector where, however, there are further problems tied to safety and energy density. This is lower for hydrogen than for conventional fuels; so it is necessary to reserve more space on board the ship and use more onerous solutions to reduce the volume, such as liquefaction at low temperatures, high pressure compression, the combination with other elements ([46]). Main existing barriers can be summarized in the following table.

Table 4. Barriers to the diffusion of hydrogen technology in the naval sector (source [47]).

AREA	BARRIER
Knowledge of hydrogen behavior: hydrogen handling, storage and bunkering	Uncertainties about the behavior of liquid hydrogen and the detonation thresholds in the event of leaks in closed spaces.
	Definition of rigorous risk mitigation measures: minimum sizing of spaces, positioning of fans/ventilation shafts, detectors in case of leak.
	The experience gained with natural gas cannot simply be transferred to hydrogen. The unique characteristics of hydrogen make it very different from natural gas.
	Difficulty in containing hydrogen due to the lightness of the atoms. It can cause materials that are safe for natural gas to become brittle.
Safety	Necessity to use certain types of steel and welded rather than filleted connections.
	Greater flammability than natural gas.
	Use in variable environmental conditions and in small spaces.
	Difficulty in evacuating personnel in the event of leaks/spills.
Rules/Regulations	Gaps in authorization procedures, regulations and standards regarding bunkering and the use of hydrogen as a fuel on board vessels.

Technical barriers are mainly due to the lack of in-depth knowledge on the behavior of hydrogen (particularly if liquid) and on the thresholds for triggering detonations, requiring further tests and more accurate modeling in leak scenarios in closed environments, such as those of ships, and during bunkering operations. High-speed hydrogen release, for example, may not disperse evenly, potentially resulting in formation of concentrated pockets of hydrogen and increased risk of detonation. Therefore, safety measures to avoid these eventualities will have to define the minimum dimensions of the spaces, the positioning of the fans and ventilation shafts. Some safety aspects that hinder the use of this energy carrier in navigation are linked to the specific properties of hydrogen which require specific use procedures that cannot be transferred from experience with natural gas ([48–52]). The lack of a clear legislative framework is also one of the problems which, if not resolved, could lead to delays throughout the hydrogen supply chain. Currently there is no internationally recognized regulation (in the IMO - International Maritime Organization) for the use of hydrogen as a fuel on board boats and therefore, as reference regulations, the rules in force for other types of fuels.

Due to these reasons the scenarios (Figure 8, [53]) describe a reduced future diffusion of the hydrogen watercraft solution, in favor of the use of biofuels and e-fuels (especially methanol and ammonia) which are cheaper, safer and easier to handle ([54]).

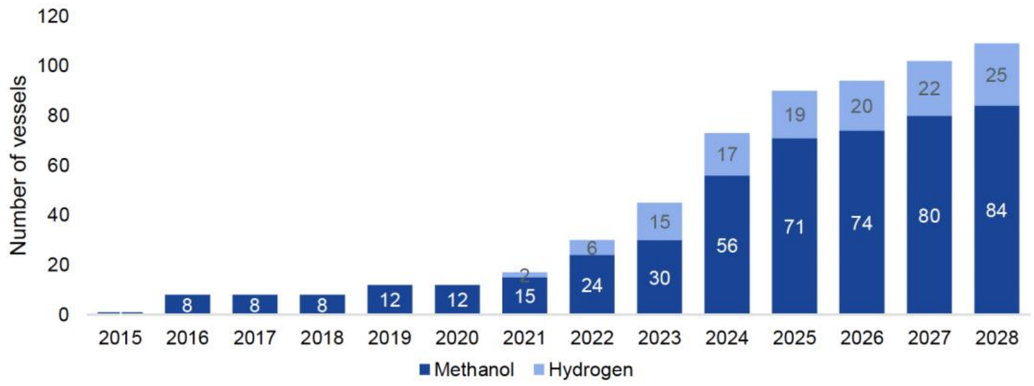

Figure 8. Annual delivery of hydrogen- and methanol-fueled vessels (source [54]).

Finally, the use of hydrogen in the aeronautical sector presently appears still too uncertain and not sufficiently mature, especially regarding the supply chain (Figure 9) to determine precise and definitive considerations in this regard, so more research and development on hydrogen as an aviation fuel is needed ([55]).

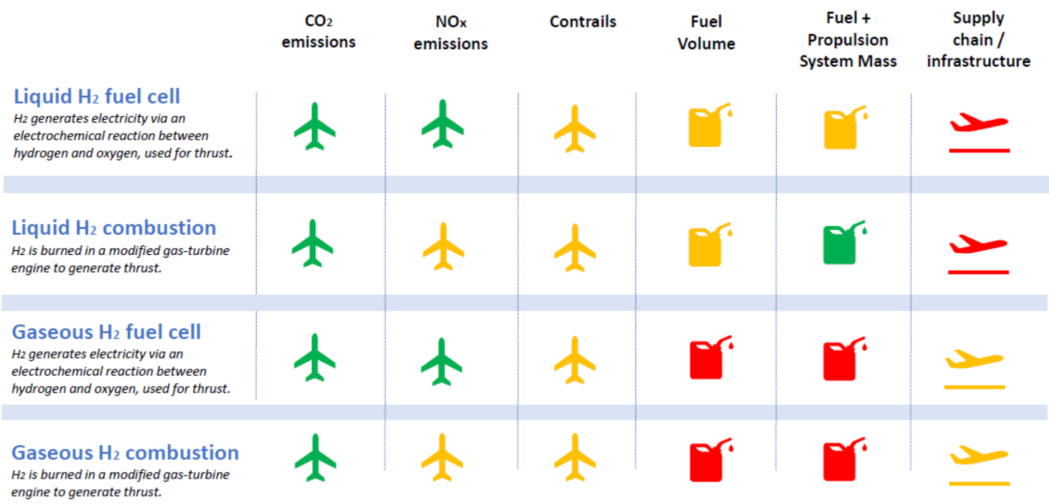

Figure 9. Pros and cons of hydrogen as aviation fuel (source [55]).

5. Hydrogen Storage and Interaction with the Electric Grid

In the context of the use of hydrogen both as a feedstock in hard-to-abate industrial processes (e.g. direct reduction process of the integral steel production cycles [56,57]) and as an energy carrier (e.g. in downstream reheaters of the steel production process), implementing hydrogen storage can

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be an important opportunity, both for the system and for the investor. The reasons may be different: linked to an improvement of the flexibility of the industrial process itself, to the possibility to overcome shortcomings in hydrogen supply, which may be intermittent or scarce compared to the quantities to be used, or, in the long term, to the opportunity of realizing profits by providing additional flexibility services to the electric grid. Industrial processes which require hydrogen as a feedstock (e.g. hard to abate sectors like steelworks) can make their production schedule more modulable and flexible if hydrogen is fed through a local storage system and this can turn into a strong advantage for the industrial production scheduling, making it easier to satisfy clients' requests. Furthermore, electric grids are characterized by reduced flexibility when coping with the need to realize an instantaneous match between power generated and the load. On the other hand, in the recent years we are witnessing a strong penetration of generation from Variable (i.e. non-programmable) Renewable Energy Sources (VRES), wind or photovoltaic solar generation (PV) in particular: it would be extremely useful to dispose of network storage elements capable of absorbing overgeneration in the electric grid while providing power to the network when generation in scarce.

A recent study by Frontier Economics and ENTSO-E ([58]) analyses compares the three present water electrolysis technologies (Alkaline (AEL), Polymer Electrolyte Membrane (PEM) and Solid Oxide Electrolyzer Cell (SOEC)) from its suitability to provide ancillary services to the electric system: Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (aFRR), Manual Frequency Restoration Reserve (mFRR), Reserve Restoration (RR), Voltage Control and Congestion Management. Both the current state of the technologies and its evolution till 2030 were taken into account. The result of the comparison is shown in Figure 10.

	Alkaline		PEM		SOEC	
	Today	2030	Today	2030	Today	2030
FCR	Yes with limits	Yes with limits	Yes with limits	Yes with limits	No	Uncertainty about flexibility
aFRR	Yes with limits	Yes with limits	Yes	Yes	No	Uncertainty about flexibility
mFRR	Yes	Yes	Yes	Yes	No	Uncertainty about flexibility
RR	Yes	Yes	Yes	Yes	No	Uncertainty about flexibility
Voltage control	Electrolysers can provide reactive power, if they are equipped with self-commutated rectifiers.					
Congestion management	Yes	Yes	Yes	Yes	No	Uncertainty about flexibility

Figure 10. Mapping of electrolysers with system services (source: [58]).

The same study ([58]) also analyses the potential for storage in Europe of large amounts of hydrogen and comes to the following conclusions:

- Europe benefits from a significant hydrogen storage potential due to the presence of important geological salt structures across the continent; these are particularly concentrated in the north of Europe.
- The estimated technical storage potential of 85,000 TWh significantly exceeds expected H_2 production from curtailed VRES in 2030 (17 to 33 TWh), but also third-party estimates of required H_2 storage in the same period (up to 70 TWh).
- However, the majority of possible sites are currently not in use and are located offshore, which may require both significant investments and medium-term timeframes before they can be commissioned. This introduces a certain degree of uncertainty about actually available storage volume by 2030.
- In addition, storage and VRES potential are unevenly distributed across Europe. Although the location of salt cavern large-scale storage sites largely coincides with Northern offshore wind potential, there are very few viable sites in the south of Europe, where the most significant PV generation potential is located.

- This could have important implications for the integration of VRES generation into existing networks in these areas, as the flexibility provided by hydrogen large-scale storage in salt cavern would be reduced and/or rely on appropriate power and/or hydrogen infrastructure to link electrolysers with demand centers and/or storage sites.

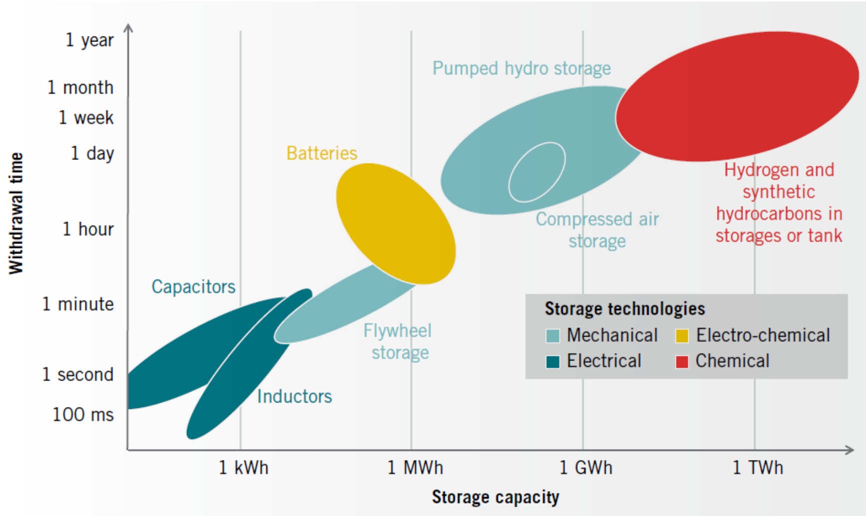

Figure 11. Capacity and withdrawal speed of different storage technologies (source: [58]).

As highlighted in Figure 11, a comparison of hydrogen with other storage technologies highlights that the former, by its nature can store large quantities of energy and, as such, is therefore even suitable for carrying out the task of seasonal storage, compensating for the different average seasonal generation renewables (summer vs. winter). However, two important points of attention should also be considered:

- Hydrogen is characterized by a Lower Heating Value (LHV) of approximately 120 MJ/kg, greater, for example, than both methane (approximately 50 MJ/kg) and petrol (approximately 45 MJ/kg). Unlike the latter, however, as it has a low density under atmospheric conditions (approximately 0.089 kg/m^3), it has a lower LHV per unit of volume, equal to approximately 10.8 MJ/Nm^3 (0.010 MJ/l). In the context of storage, hydrogen requires larger volumes than traditional fossil fuels due to its low density. To overcome this shortcoming, hydrogen can be compressed, liquefied or incorporated into energy carriers such as ammonia, methanol and other liquid organic carriers (so-called LOHC: Liquid Organic Hydrogen Carriers) [59]. However, the transformation of hydrogen in LOHC is subject to very low conversion efficiency (e.g. the efficiency of the transformation of hydrogen into ammonia is only 29%), which further reduces the already low efficiency of electrolyzers - see next point.
- The transformation from electric carrier to hydrogen and vice versa occurs through electrolysis and fuel cells respectively. As it already happened in the renewables sector, technologies costs are rapidly decreasing. In fact, the cost of the electrolyzers has dropped by over 60% in the last ten years and is expected to halve further by 2030 thanks to technological developments and economies of scale ([60,61]). However, the efficiency of the conversion process implemented by the electrolyzers is very low (currently 64% according to the IEA) and there are thermodynamic limits that suggest that it is not possible to achieve strong increases in efficiency with the current technologies. The efficiency of the conversion process from hydrogen to electricity, implemented by fuel cells, is also very low (around 30%). Therefore, a conversion from the electric carrier to hydrogen for storage and then back to electricity would be affected by an overall efficiency equal to the product of the efficiencies of the two processes applied in cascade (i.e. 38%). All this strongly advises against the accumulation of electrical energy in the form of hydrogen if it is then necessary to implement the reverse transformation into electrical energy unless there will be strong technological improvements in the medium to long term. In the case of electrical sectors where it is necessary to both power an electrical load and supply hydrogen as a raw material, the best option from an energy point of view is to decouple the storage elements, installing both electrolyzers and batteries in parallel.

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Obviously, everything highlighted above applies to hydrogen production processes via electrolysis. In the case of methane production via steam reformer, since the process is not electrically powered, there is no possibility of its use to capture the overgeneration of non-programmable electricity generation sources (however, obviously, it remains possible to compensate periods of reduced renewable generation).

In conclusion, hydrogen storage presents itself as an interesting opportunity where it is necessary either to fuel processes that already use it as a raw material or where there is the opportunity to store large quantities of energy produced from non-programmable renewable sources (also for the purpose of have seasonal storage). On the other hand, small-medium sized storages aimed at providing flexibility to the electricity system should be created, at the current state of conversion techniques, with means other than hydrogen. This will stay true for the short-medium term.

In the long term, coupling hydrogen storage with the electric grid will give rise to significant infrastructure planning needs. In fact, by 2050 Europe and many other Countries in the world will witness strong penetration of renewable energy generation. In summer, these plants will generate large quantities of energy which can be stored in the form of hydrogen. To this end, electrolyzers of increasing size will be installed, capable of absorbing significant quantities of renewable electricity. However, large electrolyzers are characterized by high electrical energy absorption and this will imply the need to plan significant expansion actions on certain sections of the network.

The task of absorbing renewables overgeneration and transforming it into hydrogen will mainly be taken on by the so-called hydrogen valleys, usually defined as geographical areas where several hydrogen applications are combined together into an integrated hydrogen ecosystem that consumes a significant amount of hydrogen, improving the economics behind the project ([62]), but here extended to mean localized areas where hydrogen is produced not only for local utilization but also for export through a dedicated infrastructure. In this way hydrogen valleys ideally cover the entire hydrogen value chain: production, storage, distribution and final use, These hydrogen valleys will be created as far as possible in brown field sites and in proximity to industrial districts of hard-to-abate sectors in order to limit as much as possible the costs of creating the hydrogen transport and storage infrastructures, which represent the most critical component of the entire hydrogen value chain. With the penetration of renewables and the increase in the size of electrolyzers (and, consequently, in the size of storage), it will be necessary to provide for an expansion of the current hydrogen valleys and possibly create new ones. The development of a liquid market for hydrogen will be a further element that will facilitate the diffusion of hydrogen valleys. In this way, large seasonal storage systems will be created, capable of storing excess energy during the summer to then be used during the winter to compensate for the reduction in wind and solar production. Hydrogen valleys will play a significant role in national energy security.

The large quantities of hydrogen produced in the summer periods in the hydrogen valleys will have to be distributed in the winter periods to end users, in particular the hard to abate sectors. This will make it necessary to create a dedicated network for the transport of hydrogen, possibly transformed into liquid compounds such as ammonia or methanol to facilitate its accumulation and transport, towards the centers where the hydrogen will be used. The location of hydrogen valleys next to industrial districts, while significantly reducing the need for large hydrogen transport infrastructures, will not eliminate the need to develop an infrastructure dedicated to hydrogen transport from scratch. After an initial period in which the modest quantities produced could justify transport with cylinder trailers, in the medium-long term the strong increase in production would make it economically advantageous to create a dedicated infrastructure.

Hydrogen valleys represent a valid solution for centralized production, which works synergically with delocalized production in industrial districts. Large industrial plants consuming hydrogen will choose between starting delocalized production or connecting to hydrogen transport networks from hydrogen valleys on the basis of an assessment of economic convenience, thus solving the dilemma of whether it is more convenient to transport electrons or molecules (H_2). A third solution will be possible in cases where the delocalized installation is considered economically advantageous but

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still insufficient to supply the necessary quantity of hydrogen. In this case, it will be possible to adopt a hybrid solution with both local production and connection to the hydrogen valley.

In parallel with the use of the hydrogen valley model and delocalized production, the opportunity for the European Countries to import hydrogen produced in non-European countries where the potential for renewable generation is very high (e.g. solar in North Africa) through appropriate import corridors has to be economically assessed too. For instance, the natural geographical position of Italy within Europe could lead it to become an important European "hub", so that part of the import would then be re-exported to the countries of central Europe, where a strong future demand for hydrogen. In line with these considerations, to deliver the 2030 hydrogen demand targets set by the RePowerEU plan, the European Hydrogen Backbone initiative ([63]) has been established and five large-scale pipeline corridors are envisaged ([0], see Figure 12). such corridors will initially connect local supply and demand in different parts of Europe, before expanding and connecting Europe with neighboring regions with export potential.

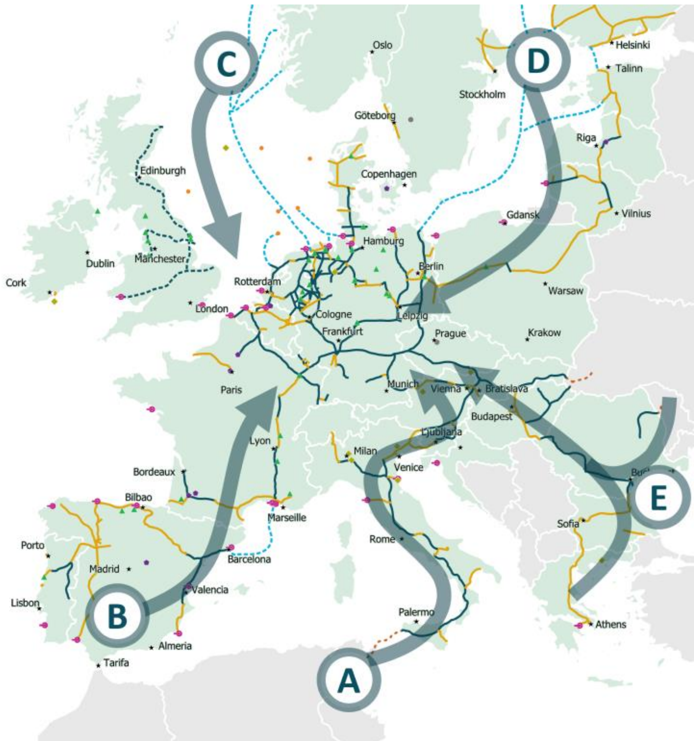

Figure 12. The five EU planned corridors for hydrogen import (source: [63]).

In the medium-long term, with the increase in the efficiency of electrolyzers and fuel cells, hydrogen storage will also be economically convenient to provide flexibility to the network (real-time ancillary services). However, even for this type of use it will be essential to develop the electricity network (transmission and distribution), so that there are no significant bottlenecks between the storage elements and the renewable generation with intermittent behavior that they would be called upon to compensate for which would prevent such use. compensation process. Obviously, from time to time it will be necessary to evaluate by means of an accurate cost-benefit analysis whether the investment in the network to remove network congestion is economically advantageous given the reduction in the price of energy on the electricity market and the removal of this would entail.

Finally, it would be appropriate to evaluate the opportunity for synergies between hydrogen production and other low-carbon technologies, such as biomethane and nuclear (possibly generated by fusion, provided this technology becomes mature in the long term), evaluating for each of them the different pros and cons from a holistic perspective.

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6. Evolution of Hydrogen Supply

Since 2017, many countries worldwide have started developing their own hydrogen strategies, supported by the zero-emission international scenarios, and considering the technologies available for hydrogen supply [65–70]. Thanks to an increasing demand, and increasing economical efforts in R&D, technological development has rapidly growth in the last decade [71–78]. Although the number of supply solutions increased, the feasibility of some production technologies is still a challenge. Clearly, this aspect is crucial for a consistent implementation into national strategies of each studied technology according to the main characteristic of the single countries (e.g., renewable potential, climate, morphological aspects of the territory).

Modern hydrogen production technologies can be divided into three main categories: thermal, electrical, and biological, as reported in Figure 13. By contrast, in the scientific literature it is proposed to change this classification system and base feasibility assessments on three aspects [72,78]:

- technology readiness level TRL (which is a widely recognized classification method for estimating the maturity of technologies [72]),
- real carbon emissions & impact,
- produced hydrogen purity level.

The three aspects above are linked to each other and synergically working for a consistent energy transition.

The TRL is essential to estimate the feasibility of a technical solution in a modern context as well as its prospect for the medium-long term evolution. Figure 13 describes the modern technologies for hydrogen production classified by technological maturity level. From this graph it is evident that a significant number of technologies is still under development, with a small set of ready-to-use solutions. Three main groups are identifiable: lower TRL (1-3), Medium (4-6), and Higher (7-9).

Low TRL represents the 41% of the technological offering nowadays, still under development, mainly composed by chemical-related processes, investigated for their potential to enhance efficiency through synergistic effects, such as with electrolysis (e.g., photolysis, sonolysis, and their combinations) [77,79–82], and by bio-fermentation processes [83–86]. Among these, 75% exhibit lowest efficiency (below 15%), with only three technologies aiming for higher efficiency, up to 85%. While these technologies are not viable for the short- to medium-term energy transition, low-TRL chemical solutions are often used in synergy with higher TRL technologies, such as alkaline electrolysis (ALK) or gasification systems, to improve efficiency. Although their application may be postponed to the long term, their potential usefulness is undeniable, and investment in R&D for these solutions can be justified. Microbial-related technologies, such as microbial biomass electrolysis, often suffer from uncontrollable performance variations. While this technology can achieve high hydrogen production efficiency, potentially up to 80% due to synergistic effects, the instability of microbial reactants reduces overall effectiveness, making it less competitive. Other low-TRL technologies, like plasma reforming and water thermolysis, have demonstrated significant potential with high efficiencies. However, they are not economically viable due to high costs and electricity demand [86,88]. Their use may only become feasible if electricity prices decrease or in specific applications, such as purple hydrogen production (water thermolysis using nuclear energy). Even countries with plans for nuclear power in their long-term energy strategies, like the USA or the UK, do not currently consider water thermolysis for hydrogen production. Instead, they prefer electrolysis powered by nuclear-generated electricity (pink hydrogen) [66,67].

Medium TRL technologies, 21% of the whole, present wide differences in terms of efficiencies (from "unknown" to 90%). These technologies, preliminarily tested at the laboratory scale, are currently under development to allow their progress from lab to commercial scale. Electrical solutions show the highest efficiency, and they represent an improvement of the water-electrolyte-based solution proposing molted carbonate or ceramic electrolytes. Although interest in these solutions oscillated during the last decades (especially for molted-carbon electrolysis cell MCEC [89,90], working at high temperatures (up to 800°C), and as reversible as the fuel cell technology, R&D efforts recently left the place to their implementation in industrial sites. Although still under

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development, Aqueous Phase Reforming (APR) is the only fully bio-based technology for hydrogen production with a high TRL. This process involves the hydrogenation of hydrocarbons derived from biomass at relatively low temperatures and pressures (200-250°C, 10-15 bar). Currently, APR is being explored for potential application in future bio-refineries, which are crucial for the modern energy transition. However, the technology remains at a pre-commercial stage [91].

Most of high-TRL technologies are commercially available, and they have been optimized during decades of application. They represent 38% of the whole, achieve the highest efficiency per category, and because of their short-term potential, it is possible to discuss them more in detail.

Some details follow for the three main categories: thermal, electrical, and biological processes:

- Thermal processes: Steam Methane Reforming (SMR) is the most common technology globally used for hydrogen production, involving the reforming of methane gas with steam. Variations of this process include the use of air or oxygen, as seen in emerging solutions such as Partial Oxidation (POX) and Auto-Thermal Reforming (ATR). In 2022, 99,7% of the global hydrogen production has been achieved using SMR [92]. The extent of low-carbon emissions from SMR, POX, or ATR largely depends on future advancements in Carbon Capture, Usage, and Storage (CCUS) technologies [78]. Many national strategies consider the transition from "grey" to "blue" hydrogen as a necessary preliminary step toward decarbonizing modern hydrogen production [65–68]. "Blue" hydrogen production, in particular, offers a commercially viable solution that is ready for deployment, requiring fewer critical raw materials (mainly nickel as a catalyst, absent in POX) [86,93]. Biomass gasification, a well-established technology originally investigated for coal gasification, has recently been proposed for hydrogen production. This process involves separating H_2 from the resulting Syngas mixture, utilizing various gasifier configurations (entrained bed, fixed bed, fluidized bed etc.). Despite being an intriguing solution due to its potential for a negative carbon emission balance, biomass gasification faces challenges. Pyrolysis within the reactor can produce liquid components such as tar [94], a mixture of compounds like benzene, toluene, aromatics hydrocarbons which can obstructs post-gasification ducts of the plant. This obstruction requires frequent substitution of filters and other components leading to increased maintenance costs and operational interruptions. These challenges currently limit the broader implementation of biomass gasification and justify the ongoing development of solutions for these issues [75,94–96];
- Electrical processes: considered as the main low carbon emitting technologies for hydrogen production, the earliest electrolysers were based on the Alkaline ALK technology. This production solution was developed in the XIX century, and it has been further refined to achieve yields up to 80%, thanks to the enhancement of the electrolytic solution's reactivity through the addition of KOH or NaOH at a 30% molar concentration (55 kWh/kg H_2) [77,86,97]. ALK electrolysers are less expensive than membrane electrolysers, such us proton exchange membrane PEM. Nickel-based electrodes are the only components classified as "critical raw materials" by the European Commission [98]. In contrast, PEM electrolysers, while more costly, offer ALK comparable performances (58 kWh/kg H_2), but produce hydrogen with a higher degree of purity. However, they contain several critical materials, including Iridium Ir and Platinium Pt for the electrodes and Titanium Ti for the double polarized layer [98,99]. Although electrolysis is a well-established solution, ALK technology suffers from efficiency drops due to rippling in the input electricity, resulting from low-efficiency rectification processes. This issue can reduce plant yield by up to 20% under low-load conditions [100–102]. Conversely, PEM performances are less compromised at variable load conditions [99]. AEM (Anion Exchange Membrane) electrolysers represent a promising hybrid solution, combining technical advantages of ALK and PEM technologies: high purity levels, high electrolysis reactivity under fluctuant input loads, with higher efficiency (53 kWh/kg H_2). However, AEM technology is still under development, with only a few examples currently available on the market [106].

Despite the extensive list of ready-to-use technologies, national strategies typically focus on a select group of the most promising solutions (highlighted with a continuous line in Figure 13). In a few cases, other technologies are also mentioned (highlighted with a dotted line in Figure 13). These additional solutions include biomass-based options, reforming processes other than steam-based

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methods, and Solid Oxide Electrolysis Cells (SOEC) electrolysers. These technologies occupy the upper right corner of Figure 13, representing a graphical area characterized by low carbon emissions, high Technology Readiness Levels (TRLs), or high efficiency, with SOEC electrolysis and biomass gasification at the two extremes. However, some technologies, such as membrane reactors and coal gasification processes, also fall within this area but are not considered in strategies, likely due to their carbon emissions. Unlike biomass gasification, these processes lack adequate carbon emission mitigation measures [104,106].

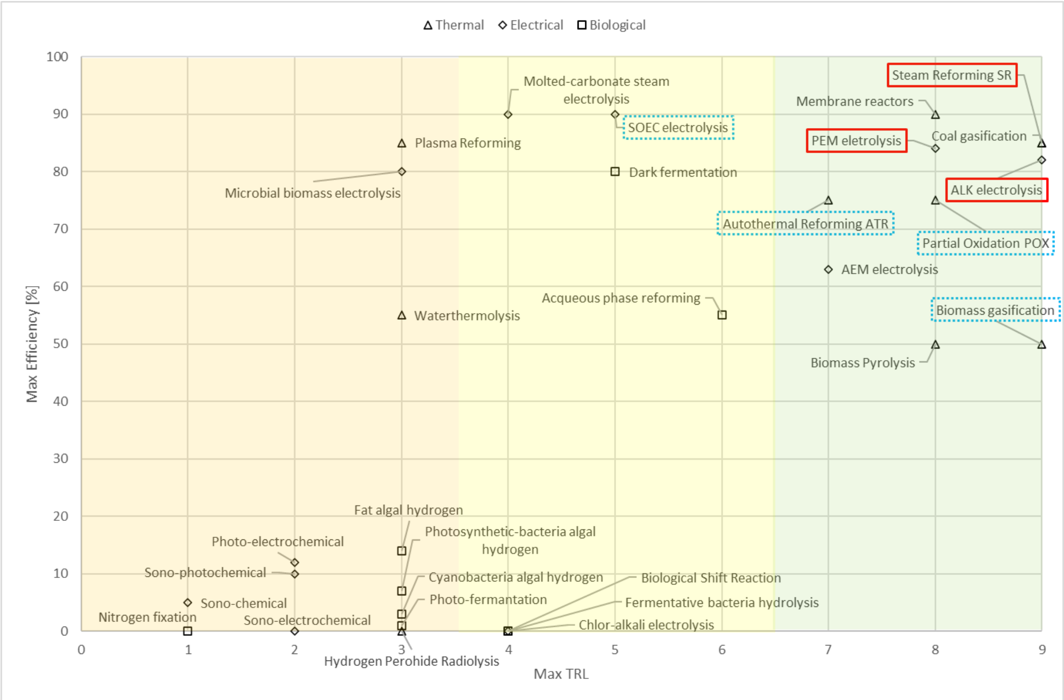

Figure 13. Hydrogen production technologies divided by max Technological Readiness Level and max efficiency reported into the literature [71–106]. Technologies are divided into the three main processes: Thermal, Electrical, and Biological. Continuous line highlighted technologies refer to those more cited in national strategies, while the dotted-line highlighted ones refer to those cited only rarely.

For high TRL technologies it is possible to define the range of levelized cost per kg of H_2 produced. Figure 14 summarizes the cost ranges for the commercialized and the most promising production technologies, as reported in the literature. As can be seen, commercial thermal solutions such as SMR has the lowest costs, and CCS presence significantly increases the cost (by up to 100%) but provide lower-carbon hydrogen. Newer technologies and their combinations, particularly those involving intermittent energy sources such as photovoltaic (PV) or wind systems tend to increase the production cost. This leads to a wider range of Levelized Cost of Hydrogen (LCOH) due to variations in annual capacity factors, which depend on the morphology and characteristics of the installation site [106,107]. Similar considerations can be made for the bio-methane reforming [108,109].

Besides the already mentioned variability of the annual capacity factor in case of renewable electrical energy production, LCOH depends on CAPEX and OPEX. In the literature [78,110], it is possible to find projections/forecasts for CAPEX of electrolysis technologies allowing perspectives on the LCOH in long-term. Figure 15 shows the trends of levelized CAPEX to stabilize around 500 CHF/kW in the long term, with a reduction by 30, 50, 70% from present costs for ALK, PEM, and SOEC technologies respectively. These reductions, followed by OPEX reductions, makes electrolysis production extremely competitive in the medium-long term.

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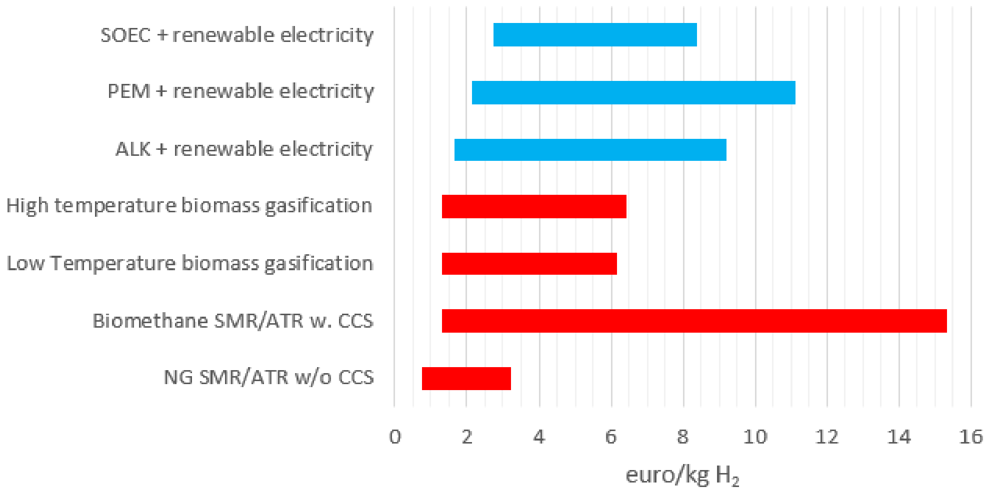

Figure 14. Levelized cost for 1 kg hydrogen production (from [78]), converted into euro (2024 1USD=0,92euro conversion rate) for the most promising technologies divided into electrical (light blue) and thermal (red) ones.

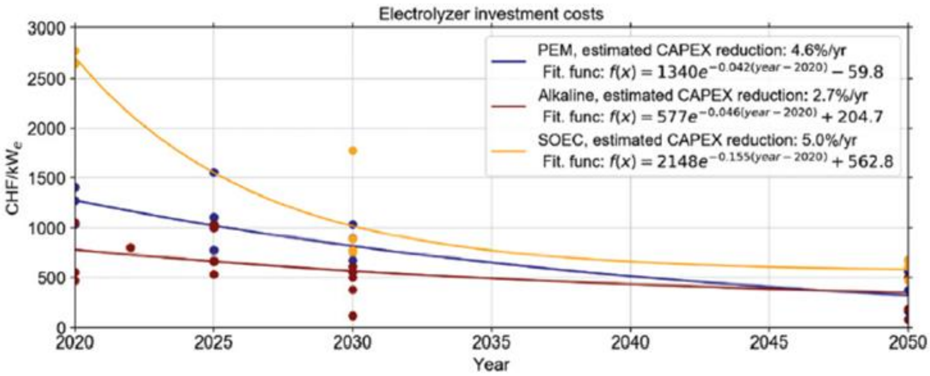

Figure 15. CAPEX projections in the medium-long terms for ALK, PEM and SOEC technologies (from [78]).

As the target of the energy transition is to decarbonize the energy sector, reaching carbon neutrality target by 2050 [3], it is extremely important to consider the actual carbon impact of the proposed commercial technologies. Recently, this approach has been emphasized in the scientific literature, raising doubts about the effectiveness of the color label scheme and its alignment with ongoing decarbonization efforts. This has led to the promotion of new carbon emission schemes that consider the Life Cycle Assessment (LCA) of the proposed technological solutions [72]. Figure 16 shows the specific emission for each high TRL H_2 production technology, highlighting the efficiency of emission reduction of CCS implementations (50% reduction for SMR). The negative contribution of biomass-based processes is attributed to LCA considerations, where biomass absorbs carbon compounds (e.g., CO_2) during its life cycle, creating a carbon credit that can exceed the emissions released during gasification [78,94,95]. Combining TRL considerations with specific emissions assessments can lead to a more effective evaluation of technological options.

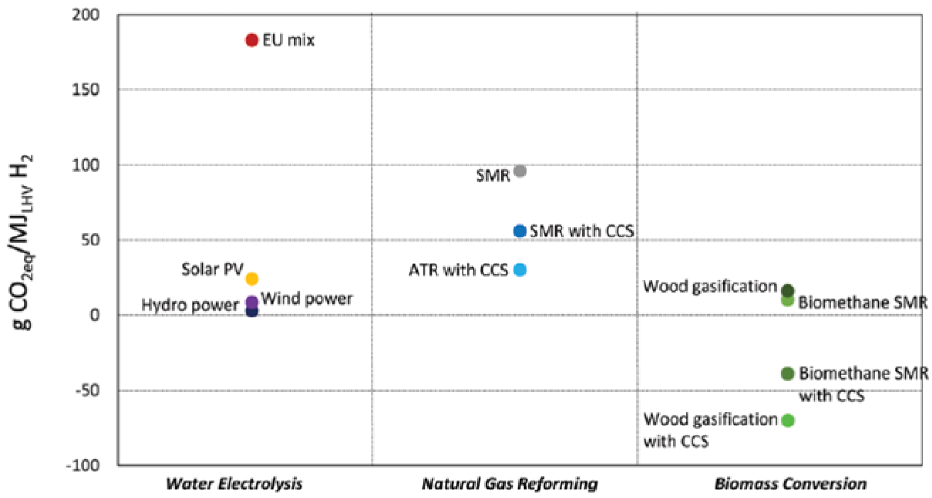

Figure 16. Specific emission for each commercial H2 production technique. PV, Hydro, and Windpower refer to electrolysis production combined by the corresponding electrical energy production (from [78]).

The purity level of the produced hydrogen is a crucial factor when determining the most suitable technological solution based on demand and specific requirements [72]. A common way to express the purity level is emerging in the literature. This parameter has been called the "number of nines" [72], referring to the number of nines in the purity level (i.e., grade 4 is equal to 99,99% of purity). This recent proxy evolved after the publication of the 2012 and 2014 hydrogen fuel product specification for vehicular and stationary use fuel cell [111]. These international standards define the possible applications of produced hydrogen in function of its purity level as reported in Table 5 in case of gaseous hydrogen applications. Interestingly, not all the hydrogen production methods match the higher purity levels reported in Table 5: for ALK, maximum purity is 99%, while AEM can achieve the 99.99%, for the highest purity grade, PEM electrolysers are required (up to 99,9999%, 1 ppm of impurities [104]). High values are also achievable by SMR (99,999%) [86], while gasification processes result in lower purity levels (biomass gasification up to 95% of purity [96]). Furthermore, standards report the maximum levels for contaminants in the gaseous mix that must be respected for functional and security reasons: biomass-based hydrogen contains more than 2 mmol/mol of CO_2 and must be treated before fuel cell use [94]. Purity levels are extremely important and must be matched with TRL and carbon impact according to demand requirements to avoid extra costs for gas post-treatment, achieving the most feasible technological solution.

Table 5. Possible applications of H2 gaseous and their potential applications in function of the required minimum purity level.

Minimum purity level	**Application**
98,00%	Internal combustion engines ICE for transport, residential and commercial combustion applications
99,90%	Industrial fuel (heat and power generation)
99,97%	Vehicular Fuel cells
99,99%	Zero grade (Fuel cell)
99,995%	Aircraft and space-vehicle ground support systems
99,999%	Ultra-high Purity grade - semiconductors applications
99,9999%	Hydrogen for research grade purpose

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Finally, from the previous analysis about the evolution of hydrogen supply based on three main aspects (TRL, emissions, and production purity), it is possible to report the following considerations:

- Although only a small group of technologies is mentioned in today's national strategies compared to the total number being investigated for hydrogen production, the most promising technologies in the medium term are those that leverage synergies with already mature technologies, allowing for performance improvements (such as the combination with electrolysis and/or gasification processes). Moreover, the general trend of decreasing prices for technologies with advanced TRL in the long term makes the implementation of these 'synergistic methods' even more promising. The strategies already demonstrate how reforming methods are excellent commercially viable solutions for CCS solutions, enabling the decarbonization of existing production and subsequently allowing the implementation of other solutions, such as coupling electrolysis (coupling with sonolysis and/or photolysis) and biomass gasification.
- It is not necessarily required to achieve the highest levels of purity for the use of the produced hydrogen. In fact, there are differences shown in Table 5 that display varying levels of purity between hydrogen produced for research purposes and hydrogen produced for applications in civilian sectors. Although this may be an inclusive factor for technologies other than PEM, improvements still need to be made to enable all technologies considered to produce hydrogen with purity levels such that it can be used without additional costs for post-production treatments (an example is biomass gasification);
- Critical materials are a risk factor for every technology involved in hydrogen production, and technologies that enable higher purity levels contain various critical materials (e.g., PEM). Despite the potential for coupling electrolysis with other phenomena, it is evident that efforts must be made to reduce the quantities of critical materials by investigating alternative materials that do not compromise the performance of the plant.
- Biomass-based production offers promising prospects in the long term, allowing for negative emissions in the lifecycle of the raw material. Nonetheless, the technology must address greater technical definition and consider that the feedstock is limited and regulated by the availability of biomass [112]. Similarly, other technologies based on renewable electrolysis also have limitations defined by the geomorphological context and geographical location (amount of wind and sunlight). This suggests that a heterogeneous technological approach, based on enhanced electrolysis and biomass, could allow for a diversification of supply, making it as dependent as possible on the seasonality of renewables and economically sustainable.

7. Hydrogen as a Commodity

The recently published EU hydrogen package, already mentioned in section 2, puts the accent on the need to create a specific market for hydrogen but doesn’t specify how this market should be created in the most efficient way.

In a first phase (low liquidity), no official market platforms will be implemented, and commercial exchanges should be regulated via Power Purchase Agreements (PPAs) and Contracts for Difference (CfDs). A PPA is a power offtake agreement between two parties, a commodity producer (e.g., electricity or hydrogen) and an offtaker of this commodity, such as a consumer or trader. A PPA includes all the terms of the agreement, such as the amount to be supplied, the negotiated price, who bears what risks, the required accounting, and the penalties if the contract is not honored. Generally, a PPA is a long-term contract, such as ten or fifteen years. It (partially) removes the risk of fluctuations in the electricity markets, which is desirable for large, debt-financed projects. For that reason, the subscription of PPAs for the electric commodity is in sharp expansion whereas the percentage of transactions passing through the day-ahead electric market is presently shrinking. The commodity can be supplied physically or virtually. In this latter case, we get a CfD, which is an arrangement made in financial derivatives trading where the differences between trade prices and a pre-established strike price are cash-settled. Both PPAs and CfDs don’t provide clear market signals to the market participants (each private trading is characterized by a different price). Thus, as soon as the hydrogen exchanges will reach a sufficient level of liquidity and the scenario uncertainties on mid-long-term evolution of hydrogen production and consumption will diminish, the need to create a centralized hydrogen platform, will emerge. Such platform, even if characterized by a reduced number of transactions, will constitute a reference for the prices at which the hydrogen commodity is exchanged, yet via PPA or CfD. Additionally, small purchases or real time adjustments of bigger positions could be more easily purchased by means of a centralized platform.

Future big owners of hydrogen production and storage infrastructures could play both in the hydrogen market and in the real time market for ancillary services of the electric grid, thus creating a coupling between the platforms and an opportunity for synergies. On the other side, the non-contemporaneity of electricity and hydrogen markets engenders a potential risk for the exercise of market power. Finally, also the gas market will get coupled with the future hydrogen market platform (as well as it already happens nowadays with the electricity market). In fact, at least in a first period, part of the produced hydrogen will be transformed into natural gas and injected in the relevant pipelines. Additionally, it is likely that in an initial phase many consumers (e.g. hard-to-abate industrial sectors) will be fed part with natural gas and part with hydrogen. So, the efficiency of the future hydrogen market will be highly influenced by its interaction with the other platforms.

The hydrogen market itself could be created in very different ways:

- as a series of cascading auctions some on the day ahead and some closer to real time,
- as a continuous market managed with peer-to-peer techniques.

Henceforth, carbon-CfDs can be implemented as a hedging tool to reduce, at least for a first period the different operative costs of green (or low carbon) hydrogen production.

Finally, at least in Europe, national platforms for electricity markets as well as national gas markets are interconnected, but the adopted architectures are fundamentally different. What should be implemented in a future hydrogen market?

Aim of the following of the present section is to carry out conceptual analysis of pros and cons of the different architectural alternatives to implement a future hydrogen market by leading for each alternative an appraisal of economic efficiency, potential to implement a seamless integration of the markets on the different carriers (electricity, gas, hydrogen) and potential risk for the exercise of market power.

To start with, it must be remarked that hydrogen is highly compressible (as it is the case for natural gas). This fact makes it easily possible to regulate, within given limits, a real time mismatch between forecasted demand and actual request by acting on the internal pipeline storage capability, which in the case of natural gas is often called linepack. By increasing or decreasing the internal pressure (yet staying within the admitted operative range) hydrogen in excess that can't be delivered can be accumulated, giving rise to a pressure increase, or hydrogen shortfalls can be accommodated by means of a pressure decrease. Consequently, there should be no point in creating a specialized ancillary services market for hydrogen (as it was not created for natural gas). This would not eliminate the need to schedule cascading auctions corresponding to day-ahead and intraday markets for the electric commodity.

As for the electric commodity, the creation of a continuous market even if it could have the positive consequence to allow the elimination of the intermediate figure of the auction manager activating mechanisms like peer-to-peer, but nonetheless risks to significantly reduce liquidity because the possibility for a sale bid and a buy offer to meet is tied to the presence of a suitable match at the very moment in which it is submitted.

An important aspect is constituted by the interaction of hydrogen producers with the electricity ancillary services market in case hydrogen storage units provide flexibility services to the electrical system: support to frequency or voltage regulation, balancing or congestion management. About the suitability of the electrolyzer technologies to provide such services we have already written in section 5. Now, we will complement this with some considerations on market design and on the analysis of possible barriers preventing electrolysers to provide (electric) services. The reported considerations are drawn from the already quoted report [58]:

- As electricity is a key input for an electrolyzer (to be provided either locally or, more likely, from the grid), electric prices are an important element to define the profitability for those who will

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invest in electrolyzers. The possibility for an electrolyzer to be useful to provide services to the electric grid strongly depends on its geographic location. Also, the availability of spare capacity beyond what has to be provided to industrial clients with which PPAs have been stipulated is, of course important. Both these factors are potentially strongly influenced by possible support mechanisms hydrogen producers will perceive, impacting strategic decisions like location, plant size, key revenue source. A business case focusing on system services may be characterized by a very high degree of uncertainty and therefore be a less viable business case with respect to other ones focused on decarbonization needs for specific industrial users.

- There are several kinds of barriers that could limit the viability of a business case tied to the provision of ancillary services by hydrogen storage owners (see Figure 17): administrative barriers, physical barriers, economic barriers.

Report [58] identifies no structural administrative barriers preventing the participation in the ancillary services for the electric grid: future issues regarding the prequalification needs or limitations on the technologies that can provide specific services must be attentively examined. Market distortions (due to lack of clear price signals, scarce incentives also due to the interaction with other support mechanisms) can limit or prevent the participation of electrolysers to electric system services. Market design is expected to address them as well as possible technological barriers (already presented in section 5). Geographical requirements of the TSOs for location-specific services (e.g., for congestion management) should be supported by an adequate market design too.

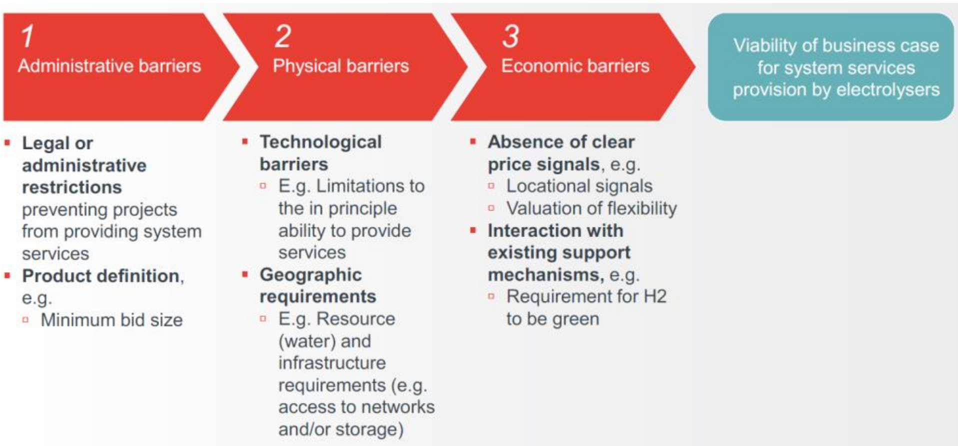

Figure 17. Taxonomy of barriers potentially impacting provision of system services of electrolyzers (source: [58]).

Very often, new technologies, like hydrogen production with electrolysers, yet suitable because generating a positive externality to the system, need to be incentivized, at last initially, in order to fill the cost gap respect to traditional technologies. Carbon-CfDs ([64]) are one of the most effective forms of incentivization that a state can provide to support greenhouse-gas-neutral manufacturing processes. These processes tend to be more expensive than the use of conventional technology but are urgently needed to decarbonise the industrial sector. CCfDs are a form of CfDs stipulated between the state and a company that adopts greenhouse-gas-neutral manufacturing processes. The CCFD covers the difference between the higher costs a company sustains by adopting greenhouse-gas-neutral technologies with respect to traditional ones. If the traditional company pays its production cost plus the cost to purchase the needed emission allowances, the CCfD gives back the difference, whenever positive, between such cost and the cost covered by the greenhouse-gas-neutral company, so that the cost gap is cancelled, and the “green” company is not disadvantaged with respect to a traditional company. This is the logics behind the Italian public consultation ([28]) already mentioned in section 2 of the present paper. Of course, CCFDs, like all forms of incentivization tend to bias trade in future hydrogen markets and for this reason should be adopted only for a temporary period while the newer “green” technologies reach maturity and, consequently, can reap upscaling advantages, which should ultimately bring to costs reduction.

Finally, it's worth mentioning that in Europe future hydrogen markets, after being created, in a first phase, autonomously in all European countries, will then highlight the need to get coupled in order to create a more liquid ecosystem and facilitate trade throughout the Continent. The same happened for electric markets, for which a coupling of the day-ahead markets has already been adopted whereas the integration of the services markets is presently on-going by means of three platforms created by ENTSO-E (TERRE, PICASSO and MARI, [114]). Of course, in order for this coupling to be effective, the market architectures in force in the different countries must be harmonized, otherwise there is a concrete risk of distortions and implicit cross-subsidizations. Considering the modalities adopted to couple the European markets, two radically different approaches have been chosen for the electricity and for the gas commodities, as well highlighted in [113]. For electricity, a seamless platform has been created by adopting a "flow based" allocation mechanism. In this way, all cross-border flows (i.e., between one state and another) are not penalized by a specific charge. By contrast, if country B is crossed by a flow originated in country A and destined to country C, this mechanism provides no remuneration for the usage of the internal network of country B, the so-called system charges, which have to do with network maintenance and grid upgrade investment costs to be covered in order to accommodate all flows efficiently and remove grid bottlenecks. This shortcoming is offset by the mechanisms of Inter-TSO compensations (ITC): this simplified algorithm allocates all cross-border flows on the so-called 'horizontal network', which includes the set of grid elements which are relevant for the exchange of energy across the EU, on the basis of the responsibility of each Member State for the use of the different network elements. This replaces the older principle on the base of which each state charges with a tariff all flows entering the border with another state. By contrast, this principle is still applied on natural gas networks and leads to the well-known "tariff pancaking" problem: a flow transiting several Countries is charged a fee each time a border is crossed. For future hydrogen network, the application of a cost reflective allocation principle similar to the one adopted in Europe for the electric grids would lead to more fair costs allocation for cross-border flows as well as will prevent "tariff pancaking", which disincentivizes any cross-border trade (which would, by contrast be extremely efficient to exploit all complementarities (e.g. areas with strong consumption by hard to abate industries and areas characterized by a strong penetration of variable RES, where the settling of hydrogen production would be very advantageous). Additionally, the adoption of different principles for quantifying cross-border transit charges in the three tightly coupled markets (electricity, natural gas and hydrogen) is likely to create externalities able to generate distortions in the relevant markets.

8. Research Needs for the Next Years

In July 2020, the European Commission defined the Strategic Research and Innovation Agenda (SRIA) [44] of the Clean Hydrogen for Europe Partnership to facilitate the transition to a decarbonized energy system. Hydrogen research aims to achieve the goals proposed in the European Green Deal, the Recovery Plan, and the activities planned under the Horizon Europe (HE) framework program, particularly through participation in calls promoted by the Clean Hydrogen for Europe, Clean Energy Transition, and Built4People partnerships.

It is essential to implement a comprehensive research and development program that covers the entire hydrogen value chain, from production to storage, from transportation to distribution, and ultimately to end uses. Research should be particularly focused on priority and strategic themes that contribute to achieving hydrogen production and penetration targets, without neglecting fundamental research.

A "permanent hydrogen research cluster" should be established, which brings together research, industry, and national stakeholders. This cluster would create a permanent tie-line between the R&D and industry by promoting a constant cross-fertilization through dedicated events organized to disseminate research results and discuss future goals, barriers, and opportunities with key representatives of the hydrogen industry.

Financial support for targeted projects with high Technology Readiness Levels (TRL) is necessary, as is supporting experimentation in key segments and the development of prototypes for the industrialization of innovative processes, with particular reference to Important Projects of Common European Interest (IPCEI) and the creation of centers of excellence for emerging research and technologies. Leveraging the opportunity to participate in numerous European funding programs, such as those promoted by the Clean Hydrogen Partnership—a partnership between the European Commission and Hydrogen Europe—to support research, development, and demonstration of innovative technologies aimed at reducing costs and increasing the competitiveness of hydrogen is crucial. Facilitating the demonstration of innovative technologies based on renewable hydrogen, exploiting opportunities from calls under the Innovation Fund of the Emission Trading Scheme and the Clean Hydrogen Alliance, in line with the provisions of the European Hydrogen Strategy, is also important.

It is advisable to set up pilot experiments for production, transmission (compression, storage, refueling), and conversion (methane, ammonia, methanol, etc.), potentially through strategic partnerships with industries. Creating synergy with industrial initiatives and local administrations to enhance the transfer of research results is also desirable. This will facilitate the creation of joint laboratories with industries and the establishment of spin-offs and start-ups. The establishment of Technological Clusters could also be an opportunity, provided they are open and competitive, to facilitate the achievement of the set objectives.

The advantages of creating large, distributed research infrastructures with a network of laboratories capable of systematizing existing capacities and equipment, adequately supported by funding and governance suited to the purpose, must be considered too. Additionally, exploiting the facilities of centers that already have a high level of specialization and can perform tests on new hydrogen technologies, promoting wide accessibility based on shared programs, is recommended.

Special attention must be given to large innovation projects (such as IPCEI, European research projects, etc.) that, with an adequate support strategy, can enable the consolidation of technological results by 2030 and their widespread application by 2050. Between 2020-2030, research should focus primarily on the so-called "hard-to-abate" sectors. Specifically, for industry, these include the chemical-petrochemical, steel, glass, cement, and paper sectors. For mobility, the focus should be on rail transport where electrification of lines is not feasible, as well as on air, maritime, and heavy road transport for long distances.

All applications already in the validation phase should be supported, such as the use of electrolyzers for grid balancing, power-to-gas, the injection of H_2 into the gas network (blending with natural gas), and the daily and seasonal storage of renewable energy surpluses. Other important areas of validation include the use of fuel cells in Combined Heat and Power (CHP) and Micro CHP systems and the production of hydrogen from the gasification of municipal solid waste (so-called circular hydrogen).

Supporting the development of electrolyzers and fuel cells to increase efficiency and reduce technology costs will be crucial. All international hydrogen strategies share three research and development objectives to which maximum effort should be dedicated:

- development of catalysts, currently primarily based on platinum group metals (PGM), with low quantities or free from critical raw materials for electrolyzers and fuel cells;
- research on advanced materials for hydrogen storage (e.g., carbon fibers, H2 carriers, etc.);
- study for an advanced understanding of the performance and durability mechanisms of electrolyzers and fuel cells.

The most important research topics for the entire hydrogen value chain are highlighted in the sub-sections below.

Production

Investments in Research and Development are necessary to accelerate the creation of electrolyzers with more efficient, economical, robust, and reliable production capacities, specifically:

- increasing the efficiency and robustness of the stack and developing high-pressure technology to reduce/eliminate the subsequent compression phase.
- developing innovative components to optimize and reduce losses and costs.

- conducting R&D activities on low-carbon hydrogen production technologies other than electrolysis:
  - production of "blue" hydrogen from hydrocarbons, with carbon capture, utilization, and storage (CCUS).
  - flexible coproduction of electricity, heat, and hydrogen from woody biomass.
  - production from biomass with negative emissions.
  - methane pyrolysis with carbon black storage.
- fostering the development of emerging technologies:
  - anion exchange membrane electrolysis (AEMEL) and proton-conducting ceramic electrolysis (PCCEL) processes.
- developing innovative materials and devices for photoelectrolysis, photoelectrocatalysis, and phonocatalysis of water (solar energy + ultrasonic mechanical stimulation) based on non-critical materials, for the direct conversion of solar energy into hydrogen or hydrogen carriers.

Storage

For short-term storage, it is necessary:

- to support the development of compression, liquefaction, absorption on solids, and new materials technologies, while for long-term storage, the study of efficient, stable, and safe solutions for injection into salt caverns, depleted gas fields, marine deposits, and resolving local methanation issues due to microorganisms in the presence of fossil carbon is required,
- to develop innovative materials for the creation of more economical and safer cryogenic tanks and cryo-compressed hydrogen technology with effective integration between fuel cells and onboard hydrogen storage in vehicles, ships, trains, and airplanes,
- to optimize and improve the efficiency of hydrogen transformation into other energy carriers such as ammonia, methanol, and e-fuels.

Transport

Here, the priority should be to develop integrated systems for transporting hydrogen to locations not in proximity to production sites. Research activities should particularly focus on materials for transport in mobile systems and the development of new, more efficient, and economical hydrogen carriers.

Utilization

On this subject, the most important R&D themes are:

- development of technologies for the use of hydrogen as a raw material in place of fossil fuels, particularly in steel production (where the technology has already reached TRL 8),
- development of technical solutions for adapting the use of hydrogen as an energy carrier in high-temperature processes in "hard to abate" sectors (upgrade and development of new burners, furnaces, etc.),
- definition of new industrial processes and prototypes involving the use of hydrogen and identification of necessary components,
- development of products in the micro-CHP (residential) and mini-CHP (commercial/tertiary) sectors that can be powered transitorily by biogas, syngas, ammonia, natural gas (blended with H2), and in perspective, with fully renewable fuels or carriers,
- research of efficient and economical applications for residential heating,
- for maritime transport: development of modular and high-power density fuel cells, as SOFC (Solid Oxide Fuel Cell) and MCFC (Molten Carbonate Fuel Cell) capable of using a diversified range of fuels and study suitable refueling solutions in ports (liquid hydrogen, hydrides, other carriers),
- for air transport: development of efficient solutions for the production of e-fuels.
- for rail and road transport: development of fuel cell technologies to increase efficiency, modularity, and cost-effectiveness.

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9. Conclusions

This paper aims at providing a thorough analysis of prospects and criticalities for the development of a solid hydrogen economy, in Europe and elsewhere in the world. It starts with an overview of the EU policy on hydrogen and national provisions. The European Union has taken hydrogen as an important pillar of its energy policy and explaining in detail the evolution of the EU regulation, with some hints on what was proposed at national level, can anyway be instructive. The subsequent paper sections describe both the demand side (i.e. the fields for which hydrogen can show a promising field of application, both as a feedstock and as an energy vector) and the offer side (evolution of hydrogen supply and production technologies). Additionally, two extra chapters deal with two topics that are rarely treated in the literature but are very important for the creation of a hydrogen economy, the former being hydrogen storage and interaction with the electric grid, the latter seeing hydrogen as a commodity and describing the main issues tied with the creation of a future liquid hydrogen market. Finally, the paper analyzes key research needs for the next years.

Throughout the entire paper, a critical approach was adopted in considering the role of hydrogen, extending the analysis on its domain of usage beyond the one of a sheer substitute for fossil fuels. Instead, we tried to reassess hydrogen's role in the light of the recent technological advancements and the practical outcomes of the various projects, which were implemented in the last four years following the launch of the European national hydrogen strategies, aiming at evaluating the achieved results comprehensively.

Numerous initiatives and projects have been launched, often spurred by a heightened enthusiasm cultivated in recent years. However, the technologies across the entire hydrogen value chain continue to face significant challenges, and cost reductions have not materialized as initially anticipated. Moreover, the regulatory framework has not consistently provided clear guidance, oscillating between stringent definitions of green hydrogen tied to specific production methods and wider interpretations of "low carbon" concepts that may permit higher levels of greenhouse gas emissions.

The production of hydrogen itself involves an inherent loss of approximately 30% of renewable electricity. Additionally, energy losses occur during storage, transportation, and utilization phases. Therefore, there is a critical need to prioritize those applications where hydrogen can deliver the greatest benefits.

Regarding the transport sector, in several countries the path to electrification for road services now seems to be firmly underway; in recent times, however, hydrogen traction is having, yet still to a small extent, a relative success and its role has been acknowledged as non-negligible in the future international de-carbonized scenarios. However, hydrogen does not appear to be a preferable option for light vehicles, at least for the next decade and perhaps even beyond. By contrast, in terms of heavy road transport, despite the overall uncertain outlook, hydrogen is considered a possible solution. Regarding local public transport, which will see a progressive replacement of the existing fleet, it is possible to expect a significant expansion in the next years, especially in local districts for production, distribution, and use of hydrogen (hydrogen valleys), where there will be availability of large quantities of hydrogen for use in FCEV buses, predictably at more competitive costs than current ones. Hydrogen can contribute to reducing emissions in the transport sector, but only if the latter is developed at a sufficiently large scale to reduce costs. Potentially interesting developments could occur in the railways and maritime sectors where, however, there are further problems tied to safety and energy density. Finally, the use of hydrogen in the aeronautical sector presently appears still too uncertain and not sufficiently mature.

On the hydrogen production side, there is a wide technological offer. However, some technologies are already mature and can help the transition (e.g. blue hydrogen), whereas others must still be fully developed to become able to replace the present ones, by increasing their efficiency levels, or having interesting characteristics (like biomasses negative emission rates). It is important to put in place an approach able to differentiate the technological offers, since no solution can be defined as the “perfect” one, but there are synergies and complementarities between different technologies (e.g. biomasses are interesting but their availability is limited; electrolysis has low emissions but must rely upon a sufficient amount of energy produced by RES). Many factors must be considered for the choice of the right technology: the final usage, the required purity level, etc. This latter parameter is very important because it allows to identify the desired improvement targets for each technology which is now under development, so as to avoid extra post-production expenses.

The hard-to-abate industry is potentially ready to boost the adoption of hydrogen both as a feedstock and as an energy vector. However, each new industrial technology must be evaluated in its potential by considering both its impact on the system (e.g. extra costs to refurbish the electrical grid) and the potential advantages that can be derive from its adoption. Additionally, the business case of the investor must also be considered, and, in case, the opportune regulatory actions must be adopted to win any reluctance to carry out the big investments which are necessary in order to adopt low-carbon technologies, involving hydrogen or not.

The adoption of hydrogen as one of the few technologies allowing to carry out seasonal storage is also very promising because this could cope with the different seasonal pattern of electric production by renewable energy sources. However, the low efficiency of the conversion processes, from electricity to hydrogen and vice versa must also be taken into account.

Finally, provided that hydrogen economy becomes sufficiently liquid, the foundation of a dedicated market will be unavoidable. Whereas in the first phases, dedicated bilateral contracts and PPA will prevail, a higher spread of hydrogen can make it interesting both to realize a dedicated transport infrastructure and the creation of a dedicated market. As this market is quite interdependent with the ones of the electricity and gas commodities, the architecture should be thought attentively in order to attain the highest allocation efficiency as well as to prevent the extensive exercise of market power from subjects which could result incumbent in the offer on one or several carriers.

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