White paper on Clean Hydrogen Production

1. Introduction

The Pathfinder project ELOBIO, funded by the European Innovation Council (EIC), has welcomed 70 experts working in 18 different countries from academia, research institutes, industry and EIC to the International Workshop on "Novel Routes to Green Hydrogen Production" on July 13, 2024, in Lyon. This workshop was a fantastic platform for knowledge exchange and collaboration. We were privileged to hear from five distinguished keynote speakers: Dr. Julie Mougin (Deputy Director for Hydrogen Technologies of CEA/Liten in France and board member of Hydrogen Europe Research for Hydrogen Production), Dr. Giuseppe Torzillo (National Research Council of Italy), Prof. Peter Strasser (Berlin Technical University), Dr. Hannah Johnson (Toyota Motor Europe) and Prof. Patrick Cognet (National Polytechnique Institute of Toulouse). Each of these experts shared their insights into different aspects of hydrogen technologies, opportunities, challenges and trends. In addition to the keynote presentations, all the participants were involved in four group discussions where both current and novel strategies for green hydrogen production were discussed. This white paper summarizes the results of the discussions about clean hydrogen technologies during this workshop, in particular on the prospects of alternative routes for its production. It also presents the main conclusions and recommendations proposed by the experts.

2. Clean Hydrogen Definition and Specifications

Hydrogen is abundant but primarily found in compounds like water and fossil fuels, necessitating extraction. Reference processes like coal gasification (brown hydrogen) and steam methane reforming (grey hydrogen) release 19 $kgCO_2/kgH_2$ and 11 $kgCO_2/kgH_2$, respectively, making them "non-clean". These technologies can be integrated with Carbon Capture and Storage (CCS) units to produce low-carbon hydrogen (blue hydrogen). However, current natural gas steam reforming processes equipped with CCS achieve a capture rate of only 60%. Additionally, there is a lack of infrastructure for CO_2 transport and storage, and finally it does not resolve the dependency towards fossil fuels. The most promising large scale production route of low carbon hydrogen is the water electrolysis technology. However, the CO_2 emissions of this process depend on electricity sources; for instance, EU's 2022 grid mix yields to 13.7 $kgCO_2/kgH_2$, worse than SMR. Hydrogen produced through electrolysis is classified as green or clean only when the electricity used comes from renewable or low-carbon sources. It is referred to as pink hydrogen when nuclear power is the energy source. In summary, there are three main types of hydrogen:

- Carbon-intensive hydrogen: Produced via processes like gasification or steam methane reforming (SMR).

- Low-carbon hydrogen: Derived from fossil fuels with carbon capture and storage (CCS) or through nuclear-powered electrolysis.
- Renewable hydrogen (also called green hydrogen): Generated via electrolysis using renewable energy sources or from biomass.

The EU Delegated Act establishes a methodology to define the conditions under which hydrogen, hydrogen-based fuels, or other energy carriers qualify as renewable or low-carbon fuels of non-biological origin (RFNBO). To meet this standard, the carbon content must be below 3.38 kg CO_2/kg H_2 over its full life cycle(Renewable Energy Directive RED III, 2023) . In contrast, the U.S. Department of Energy has set a maximum limit of 4.0 kgCO_2/kgH_2 for clean hydrogen(U.S. Department of Energy Clean Hydrogen Production Standard Guidance, 2023). Meanwhile, China has its own criteria, establishing a threshold of 4.9 kgCO_2/kgH_2 for clean and renewable hydrogen (China Hydrogen Alliance, 2020). With the anticipated growth of global hydrogen trade, establishing an international certification framework is essential to ensure transparency regarding the carbon footprint of hydrogen production.

In terms of specifications, clean hydrogen must meet standards tailored to its intended applications, encompassing purity, pressure, and transport conditions. For instance, hydrogen used in combustion for heating does not require the same purity as hydrogen intended for fuel cells or chemical catalytic production processes. Additionally, the pressure requirements vary widely: industrial applications may operate at low pressures, while transport applications often necessitate high pressures of up to 350 or even 700 bars.

In cases where hydrogen production facilities are located far away from end-users, transportation logistics require additional specifications, particularly the state of hydrogen (whether gaseous, liquid, or converted into a chemical carrier like ammonia) and pressure. Transportation can also contain risks of contamination, necessitating rigorous quality control measures to maintain the required standards for end-users.

3. Global Hydrogen Demand and Usage

As of now, the world hydrogen demand reached 97 million tons (Mt) in 2023, with the European Union (EU) accounting for about 8 Mt(Global Hydrogen Review 2024). The primary applications of hydrogen include refining and the production of fertilizers, crucial for the agriculture sector. Current hydrogen production methods are largely reliant on fossil fuels—62% through steam methane reforming and 21% via coal gasification(Global Hydrogen Review 2024) .

Future projections indicate a substantial increase in hydrogen demand, driven not only by existing industrial applications but also by emerging roles in the energy transition. Hydrogen is expected to be instrumental in decarbonizing "hard-to-abate" sectors such as steel and base chemistry. For instance, in steel production, hydrogen can replace coke in the reduction process, while in chemical, glass or metallurgic plants, it can generate high-grade heat, potentially replacing natural gas. Additionally, hydrogen is being explored as a fuel for heavy transport applications, including trucks, ships, and aircraft. In these contexts, hydrogen can either be used directly in fuel cells or internal combustion engines or indirectly to produce e-fuels in conjunction with CO_2. Finally, if produced by electrolysis, hydrogen can be seen as a means to store renewable electricity and to bring stability and flexibility to the electrical grid.

The International Energy Agency (IEA) anticipates that by 2050, global hydrogen demand could be multiplied by a factor of 5 to reach 450 Mt (Global Hydrogen Review 2024). This dramatic rise will require a fundamental shift in how hydrogen is produced, transported, and utilized. By 2030, the IEA estimates that 47% (around 70 Mt) of global hydrogen consumption will originate from clean sources, with this figure rising to an impressive 98% (approximately 420 Mt) by 2050 (Global Hydrogen Review 2024).

In response to these increasing demands, the EU's RePowerEU initiative aims to enhance energy security and sustainability. A critical element of this initiative is the commitment to double the EU's renewable hydrogen production target to 10 Mt annually by 2030, supplemented by an additional 10 Mt in imports. This strategic framework is further reinforced by policies like the Renewable Energy Directive (RED III) (Renewable Energy Directive RED III, 2023), the ReFuel EU Aviation (*ReFuelEU Aviation*, 2023)and the FuelEU Maritime initiatives (*FuelEU Maritime Initiatives*, 2023), that promote the use of renewable hydrogen.

4. Clean hydrogen production

4.1. Water electrolysis

Electrolysis technologies currently produce hydrogen at a Levelized Cost of Hydrogen (LCOH) of 5–7 €/kg H_2, with electricity accounting for the majority of the cost. These costs are expected to fall in the next decades to reach 4.4 €/Kg H_2 in 2030 and 2.7 €/Kg H_2 in 2050 (Frieden & Leker, 2024). Alkaline water electrolysers (AWE) are the most established technology which accounted for 70% of the electrolysers worldwide in 2021 (Global Hydrogen Review 2024). However, AWE have a slow response time (up to 10 minutes to start) and are then primarily used in industrial settings often paired with grid electricity. PEM water electrolysers (PEMWE), around 25% of the electrolysers worldwide in 2021, are well-suited for renewable integration with a fast and dynamic response time. Anion Exchange Membrane Water Electrolysers (AEMWE) are anticipated to mature further, potentially offering a low-cost alternative with a better adaptability to intermittent renewable electricity than AWE without using expensive noble metal catalysts (Ir, Pt) of PEMWE. However, this technology is currently at lower TRL, significant efforts are needed over the next years to improve durability and scaling. Finally, the high-temperature electrolysis, mostly Solid Oxide Electrolysers (SOE), are still in the demonstration stage. This technology offers higher efficiency (85% vs. 64% LHV) than low-temperature electrolysers by integrating external heat sources. Additionally, it can operate in co-electrolysis mode, converting steam and CO_2 into syngas, a H_2/CO mixture than can be further valorised in several chemicals and e-fuels.

Enhancing performance across different electrolysis technologies could rely on the following strategies: digital twins and scenario analysis for AWE; membrane development for AEMWE; decreasing the use of noble metal catalysts and optimizing bipolar plates for PEMWE; and improving the durability and lowering costs for SOE. Scaling these technologies requires policy reforms, financial support, fostering innovation ecosystems, automated scaling, safety standards, and efficient knowledge transfer. Lowering OPEX and CAPEX hinges on direct integration of renewable sources (wind, solar) to avoid grid fees, coupling electrolysis with energy storage, and using waste heat and materials design. Environmental impact can be reduced through critical material recycling, renewable energy use, optimized production processes, water harvesting, and decentralized production near renewable energy or end users. Clean hydrogen can have transformative applications in high-demand sectors such as steel, glass, ammonia, methanol and refineries, with supply chains integrated into energy systems to maximize the use of green electricity and minimize carbon footprints.

The production of clean hydrogen depends on the availability of essential feedstocks. For electrolysis, renewable electricity is critical, alongside water, which is its primary feedstock. While the stoichiometric requirement is approximately 9 l of water to produce 1 kg of hydrogen, practical considerations necessitate up to 18 l due to inefficiencies and auxiliary needs in the electrolyser system. This is particularly significant in light of water scarcity in many regions, especially knowing that 50% of the areas with high sun or wind potential correspond to regions with water scarcity.

Beyond the feedstocks used for hydrogen production, the materials required to manufacture production systems also warrant attention, particularly critical raw materials (CRMs) commonly used in many technologies. The EU has identified 34 CRMs—such as platinum group metals (PGMs), copper, lithium, and cobalt—and outlined specific actions in its Critical Raw Materials Act (CRM Act), including technology-specific targets. For instance, the EU aims to reduce the use of PGMs as catalysts in PEMWE. Although significant reductions in PGM usage are anticipated for PEMWE by 2030, supported by advancements in recycling processes, alternative technologies like AEMWE are drawing interest. AEMWE is expected to deliver comparable performance while requiring significantly less, or even no, PGMs. However, due to its lower technological maturity, AEMWE is unlikely to achieve large-scale deployment (GW scale) until after 2030, and possibly not until 2040. It is also the case for SOE technology, which do not use any PGMs.

4.2. Alternative production routes

4.2.1. Alternative electrolysis pathways

For decreasing the LCOH, the majority of research has been focused on how to improve current electrolyser technology via material discovery and improvements, interface engineering, cell architecture and reactor design. In parallel, multiple alternative approaches that go beyond the conventional routes have been examined. These concern mainly the low temperature electrolysis and they have been summarized as follows: (1) electrolysis using alternative feedstock, (2) assisted electrolysis, (3) operational modifications. In this section, we will discuss the advantages and merits of these alternatives approaches when compared with the conventional pathways and we will suggest future research directions.

4.2.2. Alternative feedstocks

Biomass and biogas also present viable feedstocks for hydrogen production (orange hydrogen). However, their utilisation competes with other high-value applications, especially those taking advantage of the carbon content of such molecules like for chemistry or the production of biofuels or biomethane. Thus, a thorough economic and environmental assessment is essential to determine the most beneficial use of these resources. Logistics, including the cost and feasibility of transporting feedstocks to production sites, are critical factors that must be evaluated to ensure sustainable hydrogen production. The valorisation of co-products (some biochemicals could be co-produced alongside hydrogen) is an aspect to be taken into account to improve the economic equation, similarly to the oxygen that is co-produced in the case of electrolysis. Indeed, biomass waste can be upgraded into high added-value products, coupling sustainable synthesis with circular economy schemes (Li et al., 2023) (Lepage et al., 2021). Electrocatalytic conversion of biomass and water to hydrogen and added-value oxidation products is a very promising pathway to this direction. It holds the promise to accelerate the market readiness level since both anodic and cathodic reactions could lead to valuable products. The main challenge in the field is the development of highly active and stable electrocatalyst for biomass electrooxidation reaction (BeOR). The correlation between material properties and reaction kinetics is still ambiguous, largely due to the complex reaction pathway, involving reaction steps such as dehydrogenation, adsorption/desorption of reaction intermediates, and C–C bonds cleavage (He et al., 2022). Another challenge that currently hinders the practical implementation of BeOR is the biomass degradation under extreme reaction conditions (e.g., high-temperature, basic or acidic medium), which is further aggravated for concentrated feedstocks (Zhou et al., 2023). Nevertheless, BeOR could facilitate the development of membrane-less electrolysers, as it is expected to produce no gas at the anode. Consequently, there is no theoretical need to separate the cathodic reaction, where hydrogen is generated, from the anodic reaction. This membrane-less innovative design of electrolysers can reduce cell volume and enhance the electrode area-to-electrolyte volume ratio (Sravan Kumar et al., 2025). Additionally, the absence of oxygen in the process could mitigate exposure to highly corrosive conditions, thereby improving the durability of the electrolysers. This membrane-less approach could also substantially decrease system costs, as alkaline membranes are typically expensive. However, membrane-less electrolysers might face challenges such as lower voltage efficiencies due to increased ohmic losses in the electrolyte. Another issue is the cathode's tolerance to biomass-derived molecules and its inactivity toward the electroreduction of these compounds.

Future research should seek advances in the field via electrode material development, tuning the operating conditions (e.g. single pass flow reactors), coupling BeOR with external activation knobs (e.g. light or magneto- or sono- assisted as described below) and improving our mechanistic understanding for these complex reactions.

The utilisation of seawater as an alternative feedstock, through large-scale desalination processes has emerged as a potential solution. Although the desalination step incurs a minor cost increase (approximately +$0.01/kg H_2), it must be conducted using renewable energy to maintain overall sustainability. Moreover, managing the brine produced as a by-product poses additional environmental challenges. Directly using seawater in electrolysis represents a more promising avenue. Research efforts have been directed in the development of systems that can enable direct seawater electrolysis with a minimal filtration to remove microorganisms (Frisch et al., 2023) (Dresp et al., 2019). The main challenges are the need of abundant and efficient electrode materials able to drive hydrogen evolution at the cathode and hinder chlorine evolution at the anode (Guo et al., 2023). The direct seawater electrolysis should also be competitive in terms of OPEX with the two-step counterpart. Future research should seek for advances in the field of electrode materials and membranes to enable competitive operation. Nevertheless, a first industrial demonstrator for hydrogen production from seawater electrolysis has recently started in China (Https://Hydrogentechworld.Com/Sinopec-Completes-Seawater-Hydrogen-Production-Project-at-Its-Qingdao-Refinery).

The use of wastewater is another option to be considered, but depending on its origin, wastewater can have different qualities, so that the electrolysis technology might need to be adapted case by case, thus, preventing a generic technology to be massively available and deployed at lower cost.

4.2.3. Assisted electrolysis

In assisted electrolysis approach, various external stimuli such as light, magnetic fields, and/or sonication are employed to offer operational advantages like bias free operation, enhanced reaction kinetics and overcoming mass transfer limitations via efficient bubble management.

A photoelectrochemical (PEC) water-splitting device integrates a photovoltaic cell and electrocatalysts into a single device to produce hydrogen from water using solar irradiance (Sivula & van de Krol, 2016). The major driving force behind PEC research is that it can potentially be a cost-efficient way to produce hydrogen in a renewable way. However, current PEC devices for hydrogen production are not economically viable yet (Moon & Shin, 2022). The main challenge in the field is the lack of photoelectrodes materials that can meet all the necessary requirements for water splitting, i.e. efficient light harvesting, low cost, stable operation and appropriate energy band edge position (Sivula & van de Krol, 2016). Future research should focus on two directions: (i) continue the quest for the development of efficient electrode materials for water splitting and (ii) evaluate the existing photoelectrode materials for hydrogen production via alternative feedstock like biomass or wastewater treatment (Sayama, 2018). Indeed, the photoelectrochemical conversion of biomass or wastewater into hydrogen on some photoanodes and photocathodes can be less energy demanding from the thermodynamic point of view than water electrolysis.

Performing water electrolysis in the presence of either a magnetic field or under the influence of sonication has led to performance improvements. Both approaches facilitate enhanced mass transport, thereby improving gas-liquid diffusion and assisting in the removal of bubbles from the surfaces of the electrodes (Theerthagiri et al., 2020; Vensaus et al., 2024). In addition, there are evidences that magnetic fields could enhance the electrode kinetics when magnetic electrodes materials are used (Vensaus et al., 2024) (Garcés-Pineda et al., 2019) (Mesa et al., 2024). In contrast to magneto-electrolysis and sono-electrolysis requires the supply of external power, thereby the overall energy efficiency should be evaluated (Theerthagiri et al., 2020). However, their technology readiness level (TRL) is still low, thus future research should focus on: (i) understanding the underlying mechanisms and (ii) expanding their applicability to alternative reactions like biomass oxidation, where they can act as additional activation mechanisms to improve e.g. selectivity.

4.2.4. New operating modes

In decoupled water electrolysis (DWE) oxygen evolution and hydrogen evolution reactions occur in different places, at different times and/or at rates that are not linked to each other. DWE has emerged as a disruptive concept that has spurred innovative efforts to overcome the limitations of water electrolysis (Slobodkin et al., 2024). DWE emerge as a prospective route to reduce water splitting system cost by enabling operation without expensive membranes and sealing components, providing new opportunities to reshape water electrolysis and potentially overcome the fundamental barriers.

Main challenges of DWE involve ensuring continuous and stable operation, as well as effectively scaling up the technology (Paul & Symes, 2021). In addition, this concept has been so far tested with a limited number of electrochemical reactors, leaving room for evaluating alternative approaches for driving the two distinctive steps. Future studies should aim for material stability, concept simplification and include implementation of alternative feedstock. The field can benefit from the battolyser concept, which integrates a battery and electrolyser into a single device (Mulder et al., 2017) (Hahn et al., 2024).

Another interesting approach that is worth investigating is electrolysis under dynamic conditions, also called pulsed electrolysis. In this case the application of pulsed currents or potentials are utilized for initiating chemical reactions of interest e.g., water oxidation. This concept can also be applied to biomass electrolysis. Different studies have shown that in pulsed electrolysis, selectivity towards certain products can be improved compared to steady-state operation (Miličić et al., 2023). Many groups also demonstrated that the selectivity can be tuned by the selection of pulsing profile, potential limits, as well as frequency of the change. Performance improvements have been attributed to the increase in reactant concentration at the electrode surface, the improvement of bubble detachment from the electrode, and the perturbation of the electrical double layer (Miličić et al., 2023) (Rocha et al., 2021). However, it seems that a theoretical framework to study this effect is still missing, and thus future investigations should focus in this direction as well as evaluating its role in different electrolysis processes.

Designing new architecture of reactors for performing electrolysis in another avenue of innovation. For instance, capillary fed electrolysis offers significant operations benefits such as: (i) elimination of the necessity for liquid circulation, (ii) the easier product separation, as gaseous H_2 and O_2 are generated directly in different gas collection chambers and (iii) bubble-free electrolysis system (that maintains access to the catalytic sites on the electrodes and decreases the cell resistance). However, the scalability of this technology presents significant challenges (i.e. capillary clogging or reduced efficiency in transporting the electrolyte over extended distances) that should be the main focus of future studies.

4.2.5. Innovative thermochemical and biological routes

The EU has access to diverse local feedstocks of biomass for hydrogen production, such as agricultural and forestry residues, industrial byproducts, and wastewater treatment plant outputs. The valorization of these local sources of biomass can support regional decarbonization efforts. Hydrogen can be produced from biomass through various technologies, including biological methods (dark fermentation, photo-fermentation, bio-photolysis), thermochemical processes (gasification, biomethane steam reforming, pyrolysis), and bio-electrochemical approaches (microbial electrolysis).

Among these cutting-edge approaches, gasification and pyrolysis are the most mature processes as they reached TRL 5-6 (Global Hydrogen Review 2024). Gasification involves chemical transformation at high temperatures (700–1200 °C) in controlled oxygen conditions, yielding syngas mixture (H_2, CO) and methane. Pyrolysis, conducted without oxygen at 400–1000 °C, produces biochar, bio-oil, and syngas, with biochar offering additional value as a soil amendment. Gasification is the most mature technology, while pyrolysis mostly relies on bio-oil industry. Competitive hydrogen costs could be achieved by these technologies (€4.3 to €5.8 per kg H_2 using woody biowaste) with potential biochar by-product revenues (estimated at €100–800/t) for the pyrolysis route. In addition, these processes exhibit low GHG (Green House Gas) intensity depending on the feedstock (1.8 $kgCO_2/kg\ H_2$ for wood waste). However, many barriers remain, such as the biomass feedstock availability and variability, catalyst degradation and heat recovery.

Gasification and pyrolysis can also be used to valorize non-biologic wastes, such as non-recyclable plastic waste, municipal waste, textiles, rubber, and tires, for producing hydrogen. These processes, particularly steam gasification and pyrolysis combined with reforming, are modular and scalable, making them suitable for localized applications. The estimated cost of hydrogen production is around 5 €/kg H_2 when using non-recyclable plastic waste. These methods have low GHG intensity and can even achieve negative emissions if waste is diverted from landfills. These technologies can contribute to local decarbonization by reducing landfilling and incineration. However, barriers include limited local feedstock availability, which may not support large-scale production, and competition with the chemical industry for certain waste streams.

The pyrolysis or splitting of methane is an endothermic high-temperature process for the production of both hydrogen and carbon-based catalysts such as carbon black, graphite, carbon nanotubes, and nanofibers, depending on the temperature and catalysts used. There are three main categories of methane splitting: thermal (>1000°C), catalytic (using Ni, Fe, or carbon-based catalysts), and plasma-based methods (thermal or electrochemical (electric discharge)). Although currently in demonstration or early commercial stages, this technology faces challenges such as H_2 purity, variability in the form and quality of solid carbon, high energy consumption, reactor durability, catalyst costs, and the need for transitioning from batch to continuous reactors. Despite these barriers, methane pyrolysis has significant advantages, including the availability of feedstocks and existing pipeline infrastructure. It also provides a source of materials crucial for the energy transition, such as graphite for batteries and carbon fibers for hydrogen tanks, with carbon black revenues. Additionally, biomethane and bio-propane can serve as feedstocks. GHG emissions depend on the source of gas and electricity. EU regulations do not currently recognize solid carbon from CH_4 splitting as a valid carbon capture and utilization (CCU) technology.

Photobiological hydrogen production using microalgae is a promising sustainable process, though currently at a low TRL. Certain types of microalgae can produce hydrogen as a byproduct of their metabolic activities under specific conditions. For instance, microalgae such as Synechocystis utilize two natural catalysts: Photosystem II (PSII), which splits water during photosynthesis to produce protons and electrons, and hydrogenase, which combines these protons and electrons to produce hydrogen in oxygen-deprived conditions. Microalgae represent a renewable biomass source, with their cultivation yield depending primarily on temperature and light availability. However, for microalgae biomass to become a widely available commodity, significant advancements are required. These include increasing the light conversion efficiency to hydrogen from the current 1% to at least 10% and identifying a hydrogenase enzyme that is tolerant to high oxygen concentrations (up to 400% of saturation), a common challenge in closed photobioreactors. One of the major advantages of cultivating microalgae is that they do not compete with conventional agriculture for arable land. They can be grown in desert areas, on saline soils, and with non-potable water, including wastewater. Moreover, their cultivation does not require pesticides or fertilizers. The main challenges for the scientific community include improving light conversion efficiency, overcoming the sensitivity of hydrogenase (and nitrogenase) to high oxygen concentrations, and addressing scalability issues through the development of efficient photobioreactors.

5. Transport and Storage Solutions

Transporting hydrogen involves a variety of methods, each with distinct advantages and challenges. Pipeline transport, particularly through retrofitted infrastructure, is often the most cost-effective approach. The European Hydrogen Backbone plan aims to establish 53,000 km of hydrogen pipelines by 2040, 69% being retrofitted, 31% new. Ready4H2 project indicates that more than 1 million km of distribution pipelines is material ready for hydrogen, but other components installed on the network might be less ready (e.g., compressors, valves, etc.). Transport network is composed of pipes of different metallic grades and of different ages that complicate its direct retrofitting to hydrogen, though mitigation strategies can exist. Therefore, some studies at material level are still needed (hydrogen embrittlement, coatings development…) as well as some technological verifications or optimisation for the various components that are located on the thousands of km of network. Leakage of hydrogen from this network needs to be minimized as much as possible for environmental and economical evident reasons. This challenge also requires studies at material and component levels and subsequent developments to overcome possible leakages, by improving sealings and developing H_2 sensors.

For longer-distance transport, between different continents for instance in the frame of international import/export trading of hydrogen, gaseous hydrogen is not feasible for density related aspects. Therefore, liquefied hydrogen is developed, especially for maritime shipping routes, such as those between Australia and Japan. However, alternatives like ammonia and methanol are also being considered. Each of these carriers presents unique logistical and safety challenges that must be addressed through comprehensive risk assessments and safety protocols. Liquid Organic Hydrogen Carriers (LOHC), sometimes considered for shipping transportation, can rather be envisaged as a solution for long term storage rather than a transportation carrier.

The choice of transport method significantly impacts the hydrogen costs. Pipelines are by far the cheapest option for distances up to a few 1000 km, while shipping hydrogen is the most expensive with values above \$1/kg H_2 or even \$2/kg H_2. In these conditions, the choice of the producing country needs to be done according to an important potential of wind or solar electricity to be able to produce hydrogen at very low cost (\$1-2/kg H_2) and compensate those of transportation. The geopolitical stability of hydrogen-producing countries also plays a role in the feasibility of establishing infrastructure, as uncertainties can hinder investment and planning.

Storage solutions for hydrogen must be chosen based on application requirements, including the size and duration of storage needs. Underground storage offers an economical solution for large quantities of hydrogen over extended periods, with projected costs potentially dropping below \$1/kg H_2 in the future. However, not all locations are suitable for such storage, necessitating careful site selection and planning. To conclude, there might be a trade-off between large centralized production units able to produce hydrogen at low cost, but inducing long and costly transportation pathways, and smaller localized units closer to the consumer, that would minimize the transportation cost, but having potentially a higher production cost due to the fact that smaller units lead to higher hydrogen cost and because local electricity might be more expensive.

6. Concluding remarks and recommendations

The future of hydrogen appears poised for significant growth as it becomes an increasingly critical component of global decarbonization strategies. By addressing production challenges, optimizing resource utilization, establishing clear specifications, and developing robust transport and storage solutions, stakeholders can create a sustainable hydrogen economy. Ongoing collaboration among governments, industry leaders, and the public will be vital to navigate the complexities of this evolving landscape and fully unlock the potential of clean hydrogen as a cornerstone of a sustainable energy future. Initiatives like Hydrogen Valleys in Europe and Hydrogen Hubs in the U.S. aim to foster collaboration among stakeholders, including technology providers, project developers, and local communities, thereby promoting the adoption of hydrogen solutions at various scales. Despite the promising outlook for hydrogen demand, several barriers could impede progress in the sector:

- A significant effort must be undertaken in the next decade to achieve the Net Zero by 2050, which will require, according to BloombergNEF's New Energy Outlook (New Energy Outlook 2025, n.d.), the production in EU of 34 million tons of hydrogen by 2040 and 54 million tons by 2050.
- Technical challenges related to the reliability and scalability of production technologies may deter investments. For instance, a rapid scaling of unproven technologies could result in failures that undermine confidence among potential investors.
- Economic factors also play a crucial role in the adoption of hydrogen technologies. High capital and operational costs remain significant hurdles that can restrict market entry for many players. The mismatch between the growing development of the manufacturing electrolyser capacity and insufficient installation capacity can be explained by long authorization times and a lack of funding. Therefore, financial incentives, such as the U.S. Inflation Reduction Act and the European Hydrogen Bank, are vital to encourage investment in clean hydrogen production facilities.
- The regulatory framework is often unclear and varies significantly between countries. This lack of harmonization can slow the deployment of hydrogen technologies, as different jurisdictions may require distinct permitting processes and compliance measures. The establishment of a clear and consistent regulatory framework is essential to facilitate the rapid replication of successful projects across regions. Furthermore, the legislation on critical raw materials hinders the growth of emerging technologies beyond TRL-2 stage. Regulations on the use of genetically modified microorganisms are also an impediment for biologic routes.
- The public acceptance and engagement are also critical for the successful integration of hydrogen technologies into everyday life.

This prospect highlights numerous avenues for innovation in hydrogen production, including breakthrough concepts in assisted electrolysis, alternative methods for operating electrolysers, novel electrolyser architectures, and the utilisation of bio-based feedstocks, seawater, and waste, as well as biological and thermochemical processes. The scientific challenges associated with each of these potential innovation pathways, as identified in this white paper, demand significant research efforts that should address the entire value chain of the targeted processes: technological, environmental, economic, and social. To advance these innovations, substantial investment in high-risk research and innovation is crucial. Priority areas include the development of CRM-free catalysts, the exploration of alternative feedstocks (e.g., biomass, waste, or seawater), alternative thermochemical and biological hydrogen production pathways, as well as new operating modes and architectures for electrolysers.

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