

Updates on Hydrogen Value Chain: A Strategic Roadmap

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Abstract

A strategic roadmap for non-carbonized fuels is a global priority, and the reduction of CO₂ emissions is a key focus of the Paris Agreement to mitigate the effects of rising temperatures. In this context, hydrogen (H₂) is a promising non-carbonized fuel, but the pace of its implementation will depend on the engineering advancements made at each step of its value chain. To accelerate its adoption, various applications of hydrogen across industries, transport, power, and building sectors have been identified, where it can be used as a feedstock, fuel, or energy carrier and storage. However, widespread usage of hydrogen will depend on its political, industrial, and social acceptance. It is essential to carefully assess the hydrogen value chain and compare it with existing solar technologies. The major challenge to widespread adoption of hydrogen is its cost as outlined in the roadmap for hydrogen. It needs to be produced at the levelized cost of hydrogen (LCOH) of less than \$2/kg to be competitive with the established process of steam methane reforming. Therefore, this review provides a comprehensive analysis of each step of the hydrogen value chain, outlining both the current challenges and recent advances.

Keywords: hydrogen, value chain, production, transport, storage, consumption

1. Introduction

Decarbonization, strive for net zero emissions, and work to reduce our carbon footprint. These crucial actions are indispensable in addressing the climate change challenges. By embracing decarbonization

strategies and adopting sustainable practices, we can alleviate the detrimental impacts of greenhouse gas emissions and protect the well-being of the planet and future generations.

Paris agreement in 2015 introduced the "national low-carbon strategy" and has emerged as a vital instrument. This ambitious roadmap not only serves as a guiding light but also forms the bedrock for our collective endeavor to foster a low-carbon economy. The strategy framework delineates a path that advocates for the adoption of energy-efficient and the utilization of renewable energy sources.

Hydrogen (H₂) is expected to play a significant and central role in our future society, particularly within the current efforts to transition to a low-carbon economy. The main reasons why H₂ is becoming such an important commodity are:

- H₂ is a clean energy source, producing no greenhouse gas (GHG) emissions when used in fuel cells to produce electricity. This makes it an attractive alternative to fossil fuels.
- H₂ is a versatile energy carrier that can be used in a variety of applications, from fuel cells for transportation to power/heat/electricity generation and industrial processes, *e.g.*, fertilizers.
- H₂ can be used as an energy storage medium, allowing excess energy from intermittent renewable sources such as solar and wind to be stored efficiently and used when needed.
- The development of a H₂ infrastructure which encompasses production, storage, and transportation, would create new jobs and economic opportunities in the energy sector.
- The use of H₂ in transportation and other applications can support the efforts reducing GHG emissions, thereby mitigating the impact of climate change.

As described previously, the H₂ value chain consists of three primary areas: production, storage, and distribution (transport) that enable end-user consumption. **Figure 1** depicts the layout of the aforementioned fields and their interconnectivity. Yet, each stage faces unique barriers to overcome. Experts from different fields are exploring solutions to provide timely technological transfer options.

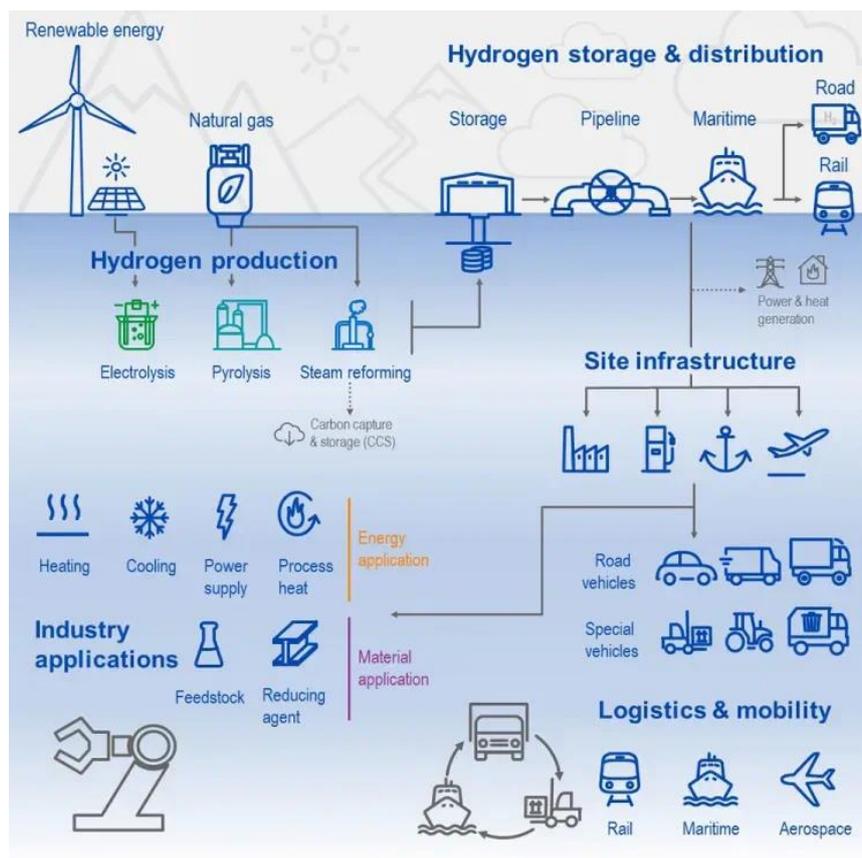


Figure 1. Scheme outlining the hydrogen value chain fields, interconnection, and roles.^[1] Copyright 2023, TÜV SÜD.

The global market demands certain maturity of emerging technologies to deliver them to the end users. Within the hydrogen economy context, the different aspects of the value chain should achieve technological readiness level (TRL) 7 or higher, to make H₂ and its infrastructures economically (and politically) attractive.

The following sections will showcase each category of the H₂ value chain, including the main associated challenges.

2. Hydrogen production

Hydrogen production has gained an enormous momentum over the last few years and will certainly play a major role in the energy transition. The reasons behind the growing importance of H₂ for our modern economy are: 1) decarbonization of energy production, in particular electricity, 2) sustainable alternative to fossil energy carriers (in particular natural gas), and 3) the lack of cost-effective energy storage of intermittent renewable energy (mostly produced in the form of electricity).

There are three main families of hydrogen production technologies that are categorized by their ‘carbon-intensity’ *i.e.*, the amount of CO₂ and CO₂-equivalents emitted during production of hydrogen. These are described in the following sub-sections in descending order of carbon-intensity.

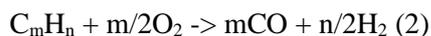
2.1. Grey hydrogen

Grey hydrogen is produced by dehydrogenation of fossil fuels. There are two main grey hydrogen production processes:

1. Reforming: hydrogen is produced by reacting a fossil fuel with steam, thereby releasing hydrogen as well as carbon monoxide, a mixture commonly referred to as ‘syngas’:



2. Partial oxidation: in this process, a fossil fuel is combusted with a sub-stoichiometric amount of oxygen, leading to the production of syngas:



Steam methane reforming (SMR) is the leading process to produce grey hydrogen. In 2021, the global hydrogen demand reached a peak of 94 Mt.^[2] Currently, about 48% of the hydrogen produced worldwide (~45 Mt in 2021) comes from SMR.^[3,4] This process consists of dehydrogenating methane (commonly from a natural gas stream) to produce a hydrogen-rich mixture, and it is the cheapest at the industrial scale. However, its environmental impact is very high: every kg of H₂ produced in this way generates around 8 kg of CO₂, indirectly.^[4] Oil and coal gasification are still heavily used, accounting for the 30% (~28 Mt) and 18% (~17 Mt) of the world’s hydrogen production in 2021, respectively.^[4] Typically, grey hydrogen production processes include additional steps (*e.g.*, water-gas shift and acid gas removal) to maximize the hydrogen yield and separate the carbon oxides from the hydrogen stream.

Among the traditional methods of producing grey hydrogen (reforming and partial oxidation), auto-thermal reforming (ATR) is used in less proportion. ATR which consists of the reforming of light alkanes (typically methane) using purified oxygen and carbon dioxide or water steam. Due to the exothermic character of reactions occurring during methane ATR the overall process has the ability of self-maintaining the reaction temperature, thereby approaching zero net enthalpy.^[5]

2.2. Blue hydrogen

The production process of blue hydrogen is similar to that of grey hydrogen; the main difference is that blue hydrogen includes the Capture and either Storage or Utilization of Carbon (CCUS). The capture of carbon consists of the separation of CO₂ from a mixture (*e.g.*, a flue gas from a combustion process

or a CO₂-rich natural gas stream) via physical or chemical means. The separation of carbon from the fuel is typically done using one of three methods:

- Pre-combustion – the carbon is separated from the fuel before being combusted, as in analogy to the SMR process
- Post-combustion – the carbon is separated after the fuel has been used to generate energy
- Oxyfuel combustion – this technology is similar to post-combustion, but oxygen is used instead of air to combust the carbon-rich fuel, leading to a more complete combustion that releases less CO and has an inherently higher efficiency.

Although there are different processes to separate the resulting CO₂, most used carbon capture processes rely on post-combustion technologies. **Table 1** showcases how post-combustion carbon capture is performed, as well as the advantages and challenges of each technology.^[6]

Table 1. Overview of the CO₂ separation technologies.

CO ₂ separation method	Description	Strengths	Challenges
Absorption	CO ₂ is absorbed in a fluid (called absorbant) that selectively binds to the CO ₂ . The CO ₂ is then released from the absorbant (regeneration) Typical absorbants: monoethanolamine (MEA) ^[6]	Mature technology, has been in use for 100 years; also known as ‘amine sweetening’, ‘acid gas removal’ or ‘amine gas treating’ (used to remove H ₂ S and CO ₂ from natural gas) Good CO ₂ selectivity High absorption rate Easy to retrofit existing plants to include it	Absorbant regeneration is energy-intensive and costly for the recovery Corrosiveness of absorbant Loss of solvent Involving toxic chemicals (aliphatic amines)
Adsorption	CO ₂ is adsorbed on the surface of a highly porous solid (called adsorbant) and later released from it (regeneration) Typical adsorbants: activated carbon, zeolites, metal-organic frameworks, carbon nanotubes	Lower energy consumption to release CO ₂ from adsorbant	Adsorbant regeneration is energy-intensive Costly adsorbant Low mass production of adsorbant No widespread industrial applications yet (moderate TRL)
Biological	Use of photosynthetic organisms for CO ₂ capture. Algae have better carbon stabilization than land plants	It preserves healthy lands, water, and air	Costly The amount of land required to scale up this technology might be high

Other technologies	Membrane separation – uses a membrane that is CO ₂ -permeable Chemical looping – using a chemical (<i>e.g.</i> , a metal oxide) to form carbonates, which can later be used to produce methane	Lower energy consumption Easier to adapt than other CO ₂ separation technologies	Scaling-up might be difficult.
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Carbon storage (or sequestration) is the process where the separated CO₂ is injected in an underground geological formation. An important characteristic of this process is that CO₂ is stored as a supercritical fluid (the critical point of CO₂ is at 31 °C and 73 bar). Therefore, not all geological sites are suitable to store the injected CO₂; often, depleted oil and gas wells are used (or at least considered), due to their ability to hold pressurized fluids. The main challenge of operating pressurized gas wells is to ensure that the gas will not escape either by permeation to the nearby soil or by displacement by another fluid (such as water). Here are a few important properties that ideal CO₂ storage reservoirs^[7] should present:

- Depth – it is recommended that the wells are at least 1 km underground to ensure that CO₂ stays in the supercritical phase (*i.e.*, to keep the pressure)
- High capillary pressure – to prevent another fluid from entering the well
- Low permeability – to prevent CO₂ from leaving the well

The main challenge of blue hydrogen (and CCUS) is primarily the social acceptance of this technology. Society views CCUS as ‘sweeping the problem under the rug’: CCUS may not constitute a long-term carbon abatement method and it is simply viewed as ‘greenwashing’ done by the oil and gas industry to maintain the current levels of fossil fuel dependency.

2.3. Green hydrogen

Green hydrogen is produced by using water and sunlight (or renewable-driven electricity). There are mainly three types of solar-driven water electrolysis processes: photocatalytic (PC) water splitting, photoelectrochemical (PEC) water splitting, and photovoltaics (PV) combined with electrolysis.^[8,9] Among the above three approaches, PV-driven water splitting already reaches relatively high TRLs (TRL 7), with recently demonstrated solar-to-hydrogen (STH) efficiencies up to about 20%.^[10] Higher efficiencies are foreseen in the near future using tandem solar cells based on improved hybrid organic-inorganic perovskite light absorbers. Recently, the certified solar to electric power conversion efficiency (PCE) tandems of lead halide perovskite with silicon has reached 32.5 %, ^[11,12] a value previously achieved only by expensive III/V semiconductors. **Figure 2** reports the *AM0* and *AM1.5* solar spectra, together with the portion of the spectrum accessible by a double junction, tandem perovskite/Si cell (see Figure 2 caption for details). The integration of the *AM1.5* spectrum up to the NIR cutoff (1107 nm) set by the Si bottom absorber returns an accessible photon flux of about $2.46 \times 10^{21} \text{ s}^{-1} \cdot \text{m}^{-2}$. Given an PCE of 30%, the photon flux effectively converted into electricity ($\sim 7.38 \times 10^{20} \text{ s}^{-1} \cdot \text{m}^{-2}$) generates a current density of almost $120 \text{ A} \cdot \text{m}^{-2}$, provided by the PV module to the electrolyzer (for this estimation, the PCE was considered equal to 30% for both absorbers in the tandem device). Hence, there is the need to develop electrocatalysts able to provide current densities of about 20 mA cm^{-2} with minimal overvoltage losses, *i.e.* less than 0.3 V for extended periods of time (months or years), using cheap and earth-abundant elements.^[13,14] The water electrolyzer therefore represents the under-developed component of this approach.^[1]

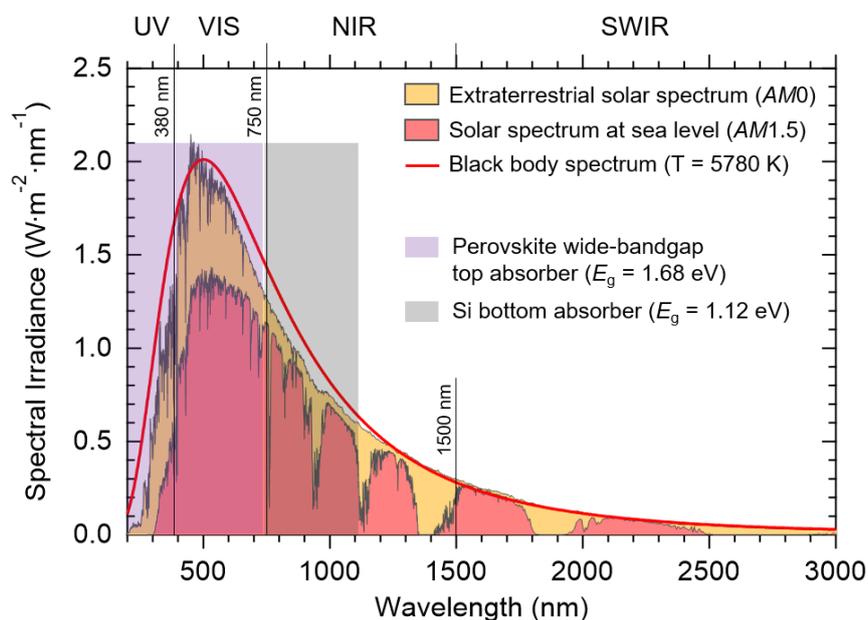
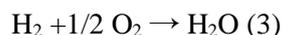


Figure 2. AM0^[15] and AM1.5^[16] solar spectra, together with the portion of the spectrum accessible by a double junction tandem perovskite/Si solar cell. In this example, the hybrid organic/inorganic perovskite is the wide-bandgap top absorber, with a bandgap of 1.68 eV^[11] (cutoff at ~ 740 nm). Single crystalline, n-type silicon is the narrow-bandgap bottom absorber, with a bandgap of 1.12 eV at room temperature^[11] (cutoff at around 1107 nm). AM: Air Mass; UV: Ultraviolet radiation; VIS: Visible radiation; NIR: Near-infrared radiation; SWIR: short wavelength infrared radiation.

Catalytic water splitting using photons or electricity occurs in a single step, as **equation 3** shows.



Water electrolysis processes have been extensively studied and reviewed in recent years, hence a vast amount of literature reviewing the processes already exists.^[17,18] Here we will only highlight the common production methods of green hydrogen, that differ in the type of charge carrier that completes the electric circuit of the electrolytic cell (**Figure 3**):

- Alkaline electrolysis – the charge carrier is OH^- . This is the most common process for producing high-purity hydrogen for uses such as in the food industry (*e.g.*, in the hydrogenation of triglycerides and fatty acids for human consumption) as well as in the current landscape of electrolytic hydrogen production for use as energy carrier.^[19] Alkaline electrolyzers have been in use since the space age (where their main use was to electrolyze water to produce O_2 for the astronauts) and they are a well-developed technology.
- PEM electrolysis – the charge carrier is H^+ . It has been developed in the past few decades using the existing knowledge from PEM fuel cells (as they share the same ion-conducting polymer membrane). PEM electrolyzers use PGM (Platinum Group Metals) as catalysts. This means that their widespread adoption could burden the supply chain of some components. However, they have an advantage over alkaline electrolyzers in their ability to quickly ramp-up and ramp-down to cope with the intermittency of renewable energy systems (RES). Thus, PEM electrolyzers are more suitable for direct connection to renewable electricity than alkaline electrolyzers. This eliminates the need to rely on the existing electricity transport infrastructure.
- SO (Solid Oxide) electrolysis – the charge carrier is O^{2-} . This is a relatively recent development that incorporates progress achieved in the SOFC (Solid Oxide Fuel Cell) industry. Whereas both alkaline and PEM electrolyzers operate at near-ambient conditions, SO electrolyzers operate at temperatures above 700°C, which implies that they are less suitable for dynamic operation. Furthermore, SO electrolyzers are at an earlier stage of development due in part to a similar status of SOFC technologies.

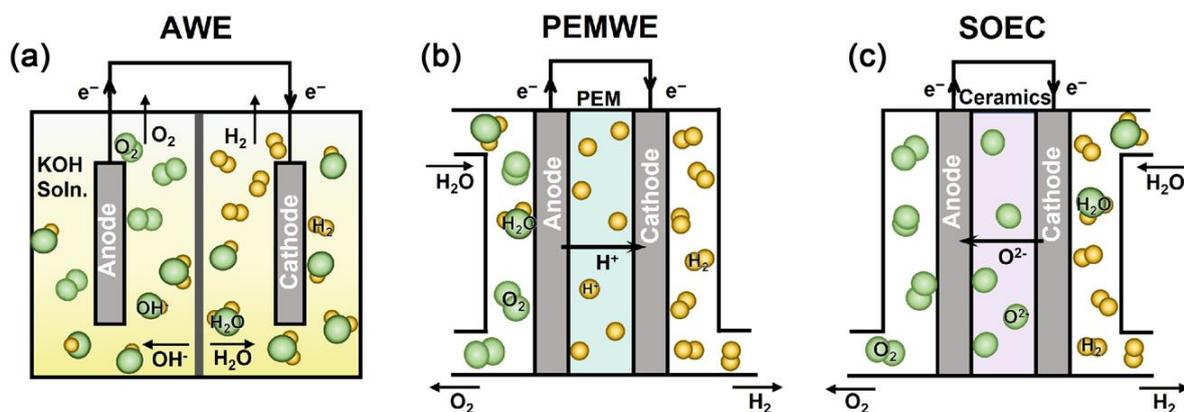


Figure 3. Schemes of (a) alkaline water electrolyzer (AWE), (b) proton exchange membrane water electrolyzer (PEMWE) and (c) solid oxide electrolysis cell (SOEC).^[71] Copyright 2022, SciOpen.

A common challenge for all types of devices described above, is the current lack of large-scale manufacture of electrolyzers, compared to the current ambitions and targets towards 2030 and beyond. As of 2020, the total worldwide electrolyzer manufacturing capacity was 20 MW/year (**Figure 4**), mostly due to electrolyzers being hand-manufactured and tailored to individual customers. According to the European strategy on hydrogen drafted by the European Union (EU) in 2020, the plan is to reach 8.2 GW of electrolyzers by 2030.^[20] The current disparity between the electrolyzers manufacturing capacity and the ambitious set targets can also be regarded as a potential windfall, given that the European interest in hydrogen could provide for a more certain panorama for private capital to invest in electrolyzer manufacture.

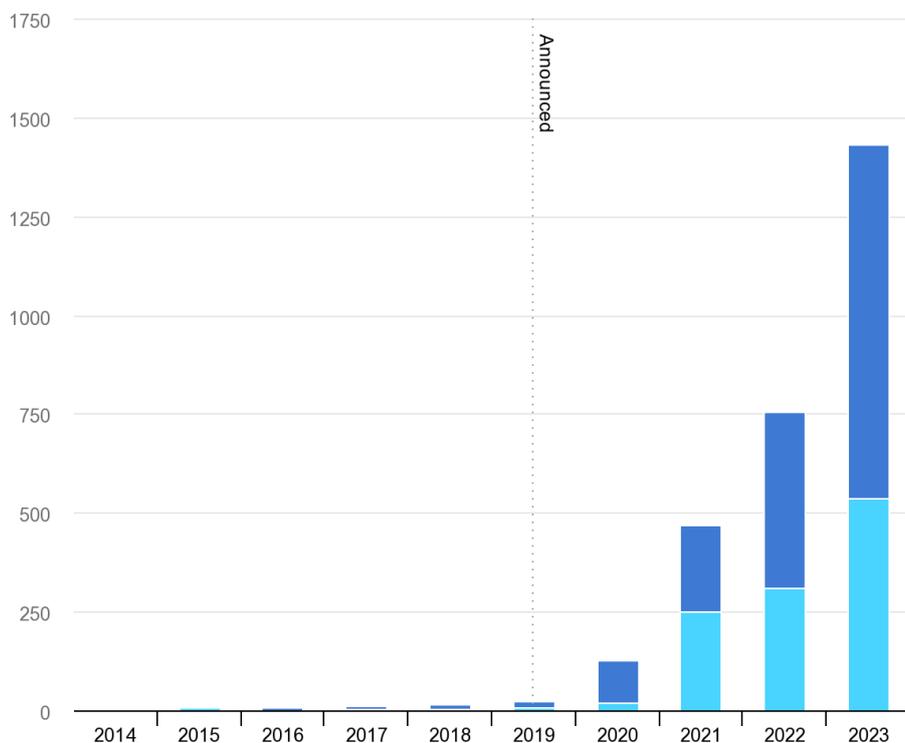


Figure 4. Global electrolysis capacity (MW/year) becoming operational annually, 2014-2023, historical and announced. Dark blue stands for total and light blue stands for largest project.^[21] Copyright 2022, IEA.

Photocatalytic- (PC) and photoelectrocatalytic-based water splitting (PEC) have lower efficiencies (<1 and 10%, respectively) compared to the PV-driven process.^[22,23] However, PC and PEC water splitting are performed using only a catalyst in powder (as suspension or adhere to an electrode), water, and

light, thereby making it a revolutionary technology due to its simplicity.^[24,25] In fact, photocatalytic water splitting is considered the "holy grail" reaction in physical chemistry, as it can directly generate H₂ from water. This is a significant advantage, as it enables the production of a solar fuel without the need for external electricity, resulting in lower operating expenses (OPEX) costs.

Photocatalysis by definition is a heterogeneous type of catalysis, requiring photons with adequate energy (see **Figure 5**) to activate the solid semiconductor/catalyst and split water into hydrogen gas.^[26-29] Extensive research efforts have been dedicated to the development of binary and multinary metal oxide light absorbers for such applications.^[30-34] This class of materials offers a wide range of optical and electronic properties, and generally shows good stability in aqueous environments.^[35] Combined with a relatively wide bandgap, this makes semiconducting transition metal oxides particularly suited as top absorbers in tandem devices. This is a promising field to explore, since for oxides containing two metal cations about 19,000 different compositions are possible^[35], only a small fraction of which has been explored to date. The highest efficiency reported for a bias-free (unassisted) tandem device with a silicon PV cell providing the lacking photovoltage along with a combination of BiVO₄ and Fe₂O₃ photoanodes achieved ca ~8%. Solar to hydrogen energy conversion efficiency ^[36].

The use of PC and PEC reactions has shown promising results in producing fuels such as hydrogen or alcohols, as well as various chemical products including fine chemicals, pharmaceuticals, and agrochemicals. However, for these processes to become a viable alternative to fossil fuels, they must overcome significant challenges such as maturity, scalability, catalyst efficiency, reactor engineering, and cost.^[37]

PC and PEC have a number of technical challenges to address, such as low photocatalytic activity, large band gap energy, fast recombination of photo-generated electrons and holes, stability problems, poor light utilization, and cost.^[38] Overcoming them requires rethinking current tendencies, concepts, and methods to enhance the understanding of the fundamentals of the technology.

Developments at the interface of materials science and engineering of chemical processes are envisaged. On the one hand, steps forward in each low (laboratory reactors), medium (pilot devices), and large (plants) TRLs are mandatory to foster larger H₂ photoproduction plants.^[22,39,40] On the other hand, rational design of efficient and stable photoabsorber/catalyst with intriguing aforementioned properties is a high demand task. The importance of this point is to consider all the eco-friendly policies and green chemistry principles to follow decarbonization guidelines. This will not be an easy task, but efforts are being made to satisfy the technological transfer demands with low CO₂ footprint materials synthesis and processes.

Given the relatively low efficiency of water splitting based on PC and PEC, these approaches should be integrated and adapted to suit specific needs, for instance for the decentralized production of hydrogen. In this context, direct seawater splitting is a promising technology, owing to the abundance and availability of seawater: about 71 percent of the Earth's surface is water-covered, with saline water accounting for 96.5% of all the water available on Earth.^[41] Moreover, 77% of all countries worldwide have direct access to seawater, a renewable resource that is constantly replenished by the natural water cycle. The use of seawater for the decentralized production of hydrogen could eliminate the need to use purified water, which can be expensive and energy-intensive to produce. Moreover, in the current scenario of water scarcity worldwide, purified water is a critical commodity: about one-in-four people (~2 billions) do not currently have access to clean, potable water.^[42] Unfortunately, this situation might worsen in the near future, due to the global warming and related climate change. Therefore, direct seawater splitting has the potential to be less reliant on centralized production facilities, making it a cheap, sustainable, and readily available option for de-centralized green hydrogen production. Cheap and Earth-abundant oxide-based semiconducting light absorbers could be pivotal for this technology: the main advantage of direct PC/PEC seawater splitting is that it does not require external sources of electricity to sustain the electrolysis, as schematically reported in **Figure 5** for a single junction device.

Instead, the process is powered directly by sunlight, which is free, abundant ($1.0 \text{ kW}\cdot\text{m}^{-2}$ at AM1.5), and renewable. In addition, due to the high concentration of NaCl in seawater ($\sim 0.5 \text{ mol}\cdot\text{L}^{-1}$)^[43], this process could provide chlorine gas as a side (anodic) product, a commodity used to disinfect water, for the sanitation of sewage and industrial waste, and for production of derived chemicals and polymers. This side production could add a significant contribution to the value chain of hydrogen.

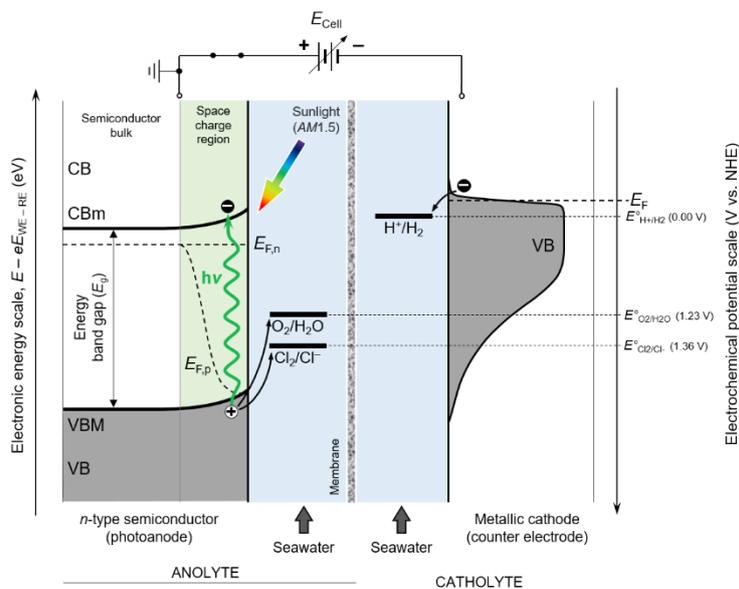


Figure 5. Schematic energy diagram of an H-type photoelectrochemical cell equipped with a single-junction semiconducting photoanode absorbing green light ($\sim 495 \text{ nm}$, 2.5 eV) immersed in seawater, under non-equilibrium conditions. Note that the energy axes are not on scale (CB: conduction band; CBm: conduction band minimum; VB: valence band; VBM: valence band maximum; E_F : Fermi level; $E_{F,n}$: Quasi Fermi level for electrons; $E_{F,p}$: Quasi Fermi level for holes; U : applied potential).

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The aforementioned green hydrogen production methods face the common challenge of high energy costs required to split water. According to thermodynamics, the energy input required for this reaction is equivalent to an applied voltage of 1.23 V. However, in practice, a voltage of more than 1.7 V must be applied to overcome the sluggish kinetics of the oxygen evolution reaction (OER),^[44] which is the bottleneck of water splitting. Even the most efficient OER electrocatalysts to date show significant overpotentials (up to 0.4 V),^[44] which leads to a significant amount of energy being spent on producing oxygen, a product with low market value. As a result, the deployment of the green hydrogen production market is hindered: green hydrogen currently accounts for only 4% of the overall production worldwide, equivalent to 3.8 Mt in 2021.^[3] Interestingly, this is in line with the amount of electricity produced worldwide using solar PV, accounting for 3.6% (179 TWh in 2021).^[45] Therefore, boosting the large-scale production of green hydrogen requires the parallel optimization and scale-up of both solar PV and electrolyzers. Value-added oxidation reactions are an attractive pathway to further reduce green hydrogen production costs by reducing energy consumption and adding market value.^[44] Biomass electrolysis offers a potential solution to replace the sluggish OER at the anodic side of (photo)electrolyzers with the more favorable organic molecule oxidation, which could lead to a more efficient production process.^[44] The hydrogen produced in this way is still considered "green" since biomass is recognized as a CO_2 -neutral, abundant, and renewable substitute for fossil fuels.^[46] Additionally, the rich proton content in most biomass building blocks makes it an effective H_2 carrier.^[44] Compared to water electrolysis, the electrolysis of biomass feedstock to generate H_2 requires less

theoretical electricity consumption, as previously reported^[47] and as schematized in **Figure 6a**. Noteworthy, the theoretical operating voltage for a device performing biomass electrolysis could be as low as 0.5 V. From a PC/PEC point of view, this voltage could be achieved with the photovoltage generated by single junction photoabsorbers, as reported in **Figure 6b**. This is a net advantage over water electrolysis, since the higher operating voltages required to split water necessitates multi-absorber tandems connected in series to yield additive photovoltages. Furthermore, biomass oxidation offers the opportunity to produce value-added chemicals, representing a highly efficient power-to-X (X = fuel and chemicals) conversion.^[44] These combined aspects have the potential to produce green hydrogen at relatively low cost, adding further value by the generation of diverse chemical commodities.

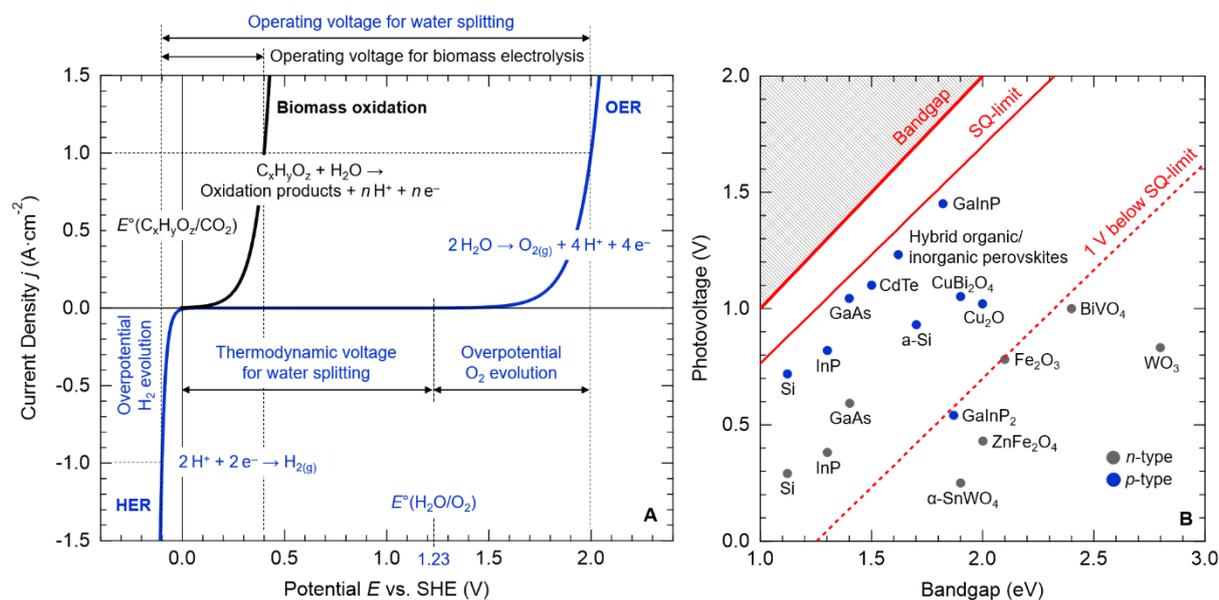


Figure 6. A: Theoretical reaction kinetics controlled by the Butler–Volmer law for water splitting and the electrolysis involving biomass oxidation. For both cases the operating voltages have been determined for a current density of 1 A·cm⁻². Adapted from C. Lamy, C. Coutanceau, S. Baranton, *Production of Clean Hydrogen by Electrochemical Reforming of Oxygenated Organic Compounds*, Academic Press, Cambridge, Massachusetts 2020. **B:** Photovoltage as a function of bandgap for selected semiconductors. The Shockley-Queisser (SQ) limit is also indicated. Adapted from Matthew T. Mayer, *Photovoltage at semiconductor–electrolyte junctions*, *Current Opinion in Electrochemistry*, 2017, 2, 104-110 (themed issue on Solar Cells edited by Michael Grätzel). HER: Hydrogen Evolution Reaction; OER: Oxygen Evolution Reaction.

3. Hydrogen transport

The existence of a transport and storage infrastructure for hydrogen could kickstart the consumption of hydrogen for all three types of consumers (in particular for mobility and the built environment). Up to this day, the amount of hydrogen consumed outside of industrial facilities is significantly low (mainly used as a reagent in research laboratories, in some captive MDV fleets, and the few available HRS worldwide before 2010). In this context, the development of the (trans)national hydrogen transport networks anywhere has not been felt by stakeholders in the hydrogen sector.

3.1. Transport of hydrogen in the existing natural gas infrastructure

The most popular method of transporting hydrogen nowadays is via the use of tube trailers, which is merely a trailer that carries a bundle of tubes and supplies gases to a particular consumer. The main disadvantage of transporting hydrogen via tube trailers is the high cost of transported hydrogen: a single tube trailer can only carry approximately 400 kg of hydrogen, and the limitation lies in the weight of the steel tubes used as well as in the maximum allowable storage pressure in tube trailers (250 bar in the U.S.).^[48]

One of the proposals that has recently gained significant attention in the hydrogen world is to repurpose the existing natural gas transmission and distribution infrastructure. Transporting hydrogen in a network that has already been commissioned would bring significant advantages including 1) a short(er) time horizon for the development of a large-scale hydrogen transport infrastructure, 2) significantly lower capital expenditures (CAPEX) of the transport system for hydrogen, and 3) to bring freedom and certainty to stakeholders on both the consumption and production sides of hydrogen, so that they can develop projects where they deem it best suited to their interests.

The retrofitting of the existing natural gas infrastructure to accommodate hydrogen comes with challenges of its own. As a first example, there could be competition with natural gas. The International Energy Agency (IEA) predicts that natural gas will continue to play a role in the global energy mix, both in the lead up to 2050 and potentially beyond.^[49] This implies that hydrogen and natural gas could compete with one another for access to the transport infrastructure; in principle, this could be solved by physically blending hydrogen in the natural gas, albeit blending also comes with its own set of risks (increased flammability of the mixture compared to pure natural gas) and challenges.

Furthermore, compatibility of the natural gas infrastructure with hydrogen can also present a difficult challenge. The development of gas transport infrastructure was historically done in view of two types of gas to deliver: 1) the transport of ‘town gas’ *i.e.*, gasified coal that consists of a mixture of carbon monoxide and hydrogen, in urban settlements, and 2) the natural gas (either low caloric or high caloric) that holds little to no hydrogen. As such, it is not expected that hydrogen would be compatible with the existing assets in the natural gas transport infrastructure, in particular looking at the transmission grid (in many countries it consists of large-diameter pipelines with a nominal operating pressure upwards of 50 bar) and being mindful of pressure-induced phenomena such as permeation, leaks, or hydrogen-induced embrittlement.

There are several past and ongoing projects^[50–54] to prove the extent to which the assets of the natural gas infrastructure can be reused for hydrogen or hydrogen blends and to which extent they would need to be replaced or maintained more often (both of which would result in increased hydrogen transport costs). Research in this topic has converged so far to the knowledge that the existing natural gas infrastructure can carry hydrogen blends up to 20-30% without serious modifications, while blending higher hydrogen percentages as well as carrying 100% hydrogen need more research.

3.2. Hydrogen shipping and hydrogen carriers

Hydrogen transportation is a crucial component in establishing a global hydrogen economy. While pipeline transport is practical for short distances, the transportation of hydrogen across oceans is necessary for long distances. The development of hydrogen shipping using various carriers, including compressed gas, liquefied hydrogen, and ammonia, presents an opportunity for countries to access clean energy sources that may not be available locally. However, several challenges need to be addressed, such as safety, cost-effectiveness, and competition with existing supply chains.

This type of transportation is known as hydrogen shipping and can be accomplished using various hydrogen carriers (**Table 2**).^[5]

Table 2. Hydrogen carriers with description, potential windfalls, and challenges.

Hydrogen carrier	Description	Potential windfalls	Challenges
Liquid hydrogen	Hydrogen is liquefied and transported using tankers to an import terminal. From there, it is transported further	The advantage of this approach is that the LNG trade is already established worldwide. Therefore, by	The primary challenge of liquid hydrogen is boil-off losses caused by imperfect insulation and quantum effects.

	inland either as a liquid or in a gaseous state.	learning from the existing LNG supply chain, the transportation of liquid hydrogen could be further developed.	
Ammonia	Hydrogen is used to synthesize ammonia but, instead of the ammonia becoming the feedstock for a further chemical process (<i>e.g.</i> , in the production of fertilizers), ammonia is shipped to a reconversion terminal where hydrogen is extracted from the ammonia and used in gaseous form.	Shipping hydrogen as ammonia can benefit from the established worldwide ammonia trade.	<p>While the Haber-Bosch process to produce ammonia is well-established, the reverse reaction to release hydrogen is still in the early stages of development. This suggests that it may take some time to develop this form of shipping.</p> <p>Furthermore, ammonia has been reported as a particularly toxic compound for humans^[55]</p> <p>Another challenge is the potential competition with the current ammonia and ammonia-derived supply chains, <i>e.g.</i>, fertilizers. This suggests that using hydrogen as an energy carrier could potentially compete with food production.</p>
Liquid organic hydrogen carrier (LOHC)	An unsaturated hydrocarbon (such as methyl cyclohexane, n-ethyl carbazole, and dibenzyl toluene) is hydrogenated to form a saturated hydrocarbon (typically in liquid form), and is later transported to a reconversion terminal where it is dehydrogenated, and the residual liquid (<i>i.e.</i> , an unsaturated hydrocarbon) is shipped back to the origin	<p>The use of LOHC can benefit from the existing worldwide trade (in particular of toluene, the dehydrogenated form of methyl cyclohexane)</p> <p>Unlike liquid hydrogen, LOHCs can be stored in liquid form at ambient conditions and, unlike ammonia, LOHCs do not pose a particularly high threat to human health</p>	<p>Whereas ammonia and liquid hydrogen are considered ‘one-way carriers’ <i>i.e.</i>, they get destroyed after extracting the hydrogen, LOHCs are meant to be two-way carriers, meaning that the dehydrogenated liquid will be shipped back to the port of origin for re-hydrogenation. This means that LOHCs are probably more suitable for short distance transport <i>e.g.</i>, between the mainland and an island, instead of being an optimal candidate for transoceanic trade.</p> <p>Both the de- and the hydrogenation of LOHCs processes are not currently done at a large scale in the world and are currently at a developmental stage, meaning that LOHC could come to the market later than the alternative hydrogen carriers</p>

Table 2 is not exhaustive. There are other hydrogen carriers at various development stages (such as methanol, alkali borohydrides, and metal hydrides)^[56], however, the three hydrogen carriers previously discussed are the most often mentioned in the hydrogen community.

In summary, the benefits of establishing a global hydrogen economy, including reducing greenhouse gas emissions, enhancing energy security, and fostering international collaboration, outweigh the challenges and make the development of hydrogen transportation a priority for a sustainable future.

4. Hydrogen storage

An important component of the supply chains of fossil fuels is the storage facilities. This is particularly relevant for gaseous fuels such as natural gas, where large-scale storage requires large volumes that can only be found underground. Storage of energy carriers is vital to the social acceptance, immediate implementation, and economy inclusion. It is also the primary method of coping with the fluctuations in supply and demand. One of the causes of the spike in the natural gas price at the end of 2021 was indeed the depletion of the European gas reservoirs that were put under stress by the decreased natural gas supply from abroad, namely Russia.

Underground storage of hydrogen can be done in a similar fashion as the underground storage of natural gas *i.e.*, in salt caverns. Salt caverns are synthetic subsurface structures that are developed by ‘washing’ away salt from an underground salt deposit until a hollow structure is formed. Salt caverns offer the most promising underground storage option due to the large sealing capacity of rock salt, its inert nature, as well as their flexibility toward injection/withdrawal cycles.^[57,58]

Although salt deposits are not commonplaces in the world, they are not particularly rare, either: there is a significant amount of salt deposits spread throughout Europe (**Figure 7**). It is estimated that the total on- and off-shore European hydrogen storage potential is 84.8 PWh_{H₂},^[57] which represents more than 8 times of the total final energy consumption in Europe in 2020.^[59] This reinforces the potential to store significant amounts of H₂ in Europe, enough to cover a potential surge in demand in the coming decades.

The investigation of underground hydrogen storage is currently underway in various regions of the world. However, this research is at an earlier stage compared to other aspects of the hydrogen value chain. Consequently, the deployment of large-scale hydrogen storage may take more time. Nevertheless, an appealing underground hydrogen storage is the H₂ project at Teesside, UK.^[60] British Petroleum and stakeholders aimed at creating the United Kingdom's first fully integrated hydrogen production and CCUS hub. The Teesside project aims to lower the industrial cluster's carbon footprint by generating blue hydrogen from natural gas, capturing the CO₂, and storing it offshore. The initiative also has economic benefits and supports the UK's net-zero emissions target.

Another clear example for the same effort is the HyStock project at Zuidwending, the Netherlands.^[61] This project particularly will investigate the effect of salt cavern storage on the purity of hydrogen and the technical feasibility (especially in safety aspects) of salt cavern storage for hydrogen.

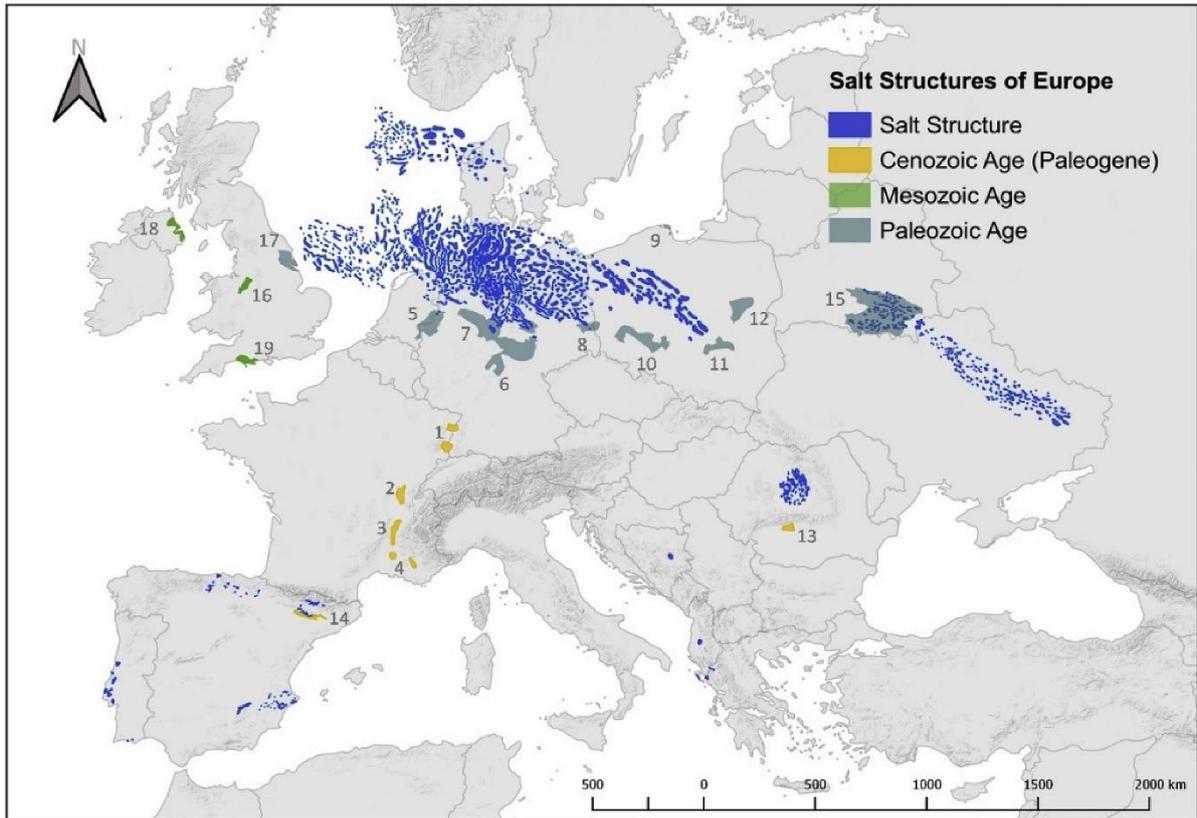


Figure 7. Salt structures localized along Europe.^[57] Copyright 2020, Elsevier.

5. Hydrogen consumption

The consumption of hydrogen to produce either (mechanical) work or heat is an important step of the value chain. Although the consumption of hydrogen has been generally associated with the operation of fuel cells, hydrogen can also be burned as any other gaseous fuel to produce heat in a boiler or stovetop as well as combustion engines for cars. Hydrogen consumption is generally divided into the types of end-users:

1. Industry
2. Mobility
3. Built environment

5.1. Hydrogen in industry

Interestingly, according to IEA, industry is the second-largest global source of CO₂ emissions (related to the energy sector, after the combustion of fossil fuels), exceeding 8.4 Gt in 2020.^[62] In particular, three heavy industries, *i.e.* chemicals (production of primary chemicals *i.e.*, ethylene, propylene, benzene, toluene, ammonia, and methanol), steel, and cement, account for nearly 60% of all energy consumption and about 72% of all the industrial CO₂ emissions.^[49]

Electrifying industry has been a viable option for years, but it has two challenges. Firstly, the cost of electricity per unit energy (MWh) is higher than fossil fuels, making it less appealing for businesses. Secondly, industrialized countries such as Germany, Poland, the US, and the Netherlands produce electricity with high carbon intensity (>300 g CO₂/kWh)^[63], making electrification ineffective in reducing industry's carbon footprint.

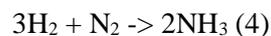
In densely populated countries like the Netherlands, the electricity grid is near its maximum transport capacity, causing congestion problems. Large off-takers and electricity producers joining the network

without a planned expansion worsen the situation. Hence, hydrogen is seen as a potential substitute for electrification. In industry, there are two primary methods for utilizing hydrogen. The first is to generate heat, primarily high-temperature heat. The second is to use it as a chemical reagent in processes such as the Haber-Bosch process for obtaining ammonia.

If heat is the main input needed by a particular industry, then in principle hydrogen can directly substitute fossil fuels such as natural gas and coal. However, current developments have pointed to potential challenges about the combustion of hydrogen:

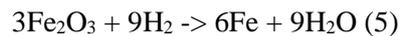
- Handling hydrogen safely requires additional attention compared to gaseous fossil fuels such as natural gas. It is necessary to ensure that the safety standards for handling hydrogen are at least as high as those for natural gas.
- Since the flame temperature of hydrogen (2180-2210°C) is higher than that of natural gas (1930-1960°C)^[64], there is a growing concern that burning hydrogen can lead to an increase in (mainly thermal) NO_x emissions as a result of the increased flame temperature. In this case, current developments in combustion technology and burner design are underway to solve this problem.

As mentioned before, hydrogen can also be used as feedstock *i.e.*, as a chemical reagent to take part in the Haber-Bosch process to produce ammonia:



Using hydrogen to produce ammonia is a well-established process. However, it has a disadvantage - hydrogen can also be obtained from natural gas through steam methane reforming (SMR).^[65] As a result, substituting hydrogen in ammonia plants is primarily a cost optimization challenge.

Hydrogen can be feedstock within the production of steel, namely the direct reduction of iron:



In steel production, the challenge is exacerbated by the existing flexibility in the current steel manufacturing processes: iron can be reduced not only with hydrogen but also with carbon monoxide, involving other types of possibly more polluting fuels such as coke-oven gas, refinery bottoms, coal, and pet coke, which can be used in the process. Eventually, the introduction of hydrogen to the industry will largely depend on its price, which will be influenced by many parameters, among them the costs of its transportation and production.

5.2. Hydrogen in mobility

Mobility has been the most discussed application of hydrogen in the past decades. Since the surge in interest by US-based car manufacturers to develop hydrogen cars in the 1990's, hydrogen has ever since been promoted as a substitute for gasoline and diesel (and to a lesser extent, for liquefied petroleum gas, LPG, and liquefied natural gas, LNG). As is the case for industrial end-users looking for a substitute to fossil-fuel combustion, hydrogen could be used in an internal combustion engine (ICE), although the vehicle would probably need to be adjusted to fit the hydrogen consumption. The other main applications for extracting energy from hydrogen are proton exchange membrane (PEM) fuel cells, considered mainly due to their higher efficiency (~50%) with respect to ICEs (~30%); the operation of PEM fuel cells has already been extensively covered in the literature.^[66] There are several kinds of mobility applications including LDVs (light-duty vehicles *i.e.*, passenger cars), MDVs (medium-duty vehicles *e.g.*, vans, public transport buses), and HDVs (heavy-duty vehicles like long-haul trucks and coaches).

Regarding LDVs, fuel cell vehicles have existed in the market for longer than a decade, with Japanese and Korean car manufacturers being the most prominent in the market. The main challenge with respect

to LDVs is the availability of hydrogen refueling stations (HRSs), although the current support for hydrogen-based mobility has accelerated the HRS market, from 330 stations available in 2017 to 540 in 2020.^[67] Besides the infrastructure availability, the cost of the LDVs fuel cell and hydrogen as fuel are considered a challenge to be overcome by the development of both suitable transport and storage infrastructure. Undeniably, the governmental policies aimed at abating carbon emissions in mobility are of great importance, too.

The requirements for introducing hydrogen for powering MDVs and HDVs are similar to LDVs, although these vehicles present challenges (in particular for HDVs) due to the more stringent operational requirements with respect to LDVs. For example, while an average LDV might drive ~20.000 km per year, a long-haul truck drives at least three times more (~60.000 km/year) and the overall number of kilometers driven with an HDV before decommissioning is significantly higher than for an LDV. The increased lifetime and operating hours of an HDV mean that the current generation of PEM fuel cells (that were perfected for LDVs as it was the primary driver for their development) cannot follow the more stringent requirements for HDVs (and some MDVs as well). In this context, there are current efforts by companies such as Hyundai, Toyota, and Nikola that seem to bridge these constraints by developing next-generation PEM fuel cells for heavy duty mobility.

5.3. Hydrogen in the built environment

The built environment, which comprises households and commercial buildings, is one of the worldwide largest carbon emitters. The Netherlands Environmental Assessment Agency reported in 2019 that the building sector emitted 12% (23.3 MtCO₂/year) of the total CO₂ emissions at the national level.^[68] Worldwide, almost 24% of the GHG emission is due to the energy production and consumption for the built environment.^[69]

Fossil fuels consumption within the built environment is primarily from cooking *i.e.*, in stovetops and ovens, or in boiler/heat exchangers to produce space heating and warm water. The challenges for introducing hydrogen into the built environment can be divided in two main categories:

- The social acceptance, where the discussion of safety is centerpiece.
- A robust transport infrastructure to supply households and commercial buildings.

The consumption of hydrogen in the built environment could be technologically feasible in time to come. Boilers and burners could be directly switched over from natural gas to hydrogen with only the addition of a safety device, meant to control the hydrogen flow to the end-user in case of failure or leak.^[70]

6. Conclusions

In order to attain the energy transition, value chain, techno-economic studies, and life cycle assessment are key tools to develop and implement synergistically evolving technologies, such as green hydrogen. Such technologies must be developed with productivity and stability as indicators. At the same time, development of hydrogen technologies should surpass their technical challenges to be able to provide reliable and competent prototype, ready and safe for the end-user. One of the major challenges is to lower the LCOH to 2\$/kg to become competitive with fossil sources. Moreover, the performance of the present state-of-the-art green hydrogen production is below par behind the 10% efficiency requirements set by industry. Therefore, extensive works are urgently required to move forward the advancement of renewable energy technologies.

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Conflict of Interest

The authors declare no conflict of interest.

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<https://sites.google.com/site/wjongresearch/>



Michael Grätzel is a Professor at EPFL where he develops photosystems for the generation of electricity and chemical fuels from sunlight. Michael graduated from the Technical University Berlin and was a postdoctoral fellow at the University of Notre Dame before joining the EPFL as a professor of physical chemistry. There, he started his groundbreaking investigations on colloidal semiconductors, which generated several new research fronts worldwide. Michael is well known for his discovery of mesoscopic dye sensitized solar cells, which in turn prompted the rise of perovskite solar cells triggering a second revolution in photovoltaics. Michael's pioneering work was recognized by a number of awards. He is a member of several learned societies

and received 12 honorary doctor degrees from European and Asian Universities. His over 1800 publications had a major impact on the photovoltaic field. A recent bibliometric ranking by Stanford University places Michael first amongst 100'000 world-wide leading scientists across all areas of science. According to the Web of Science (2022), he is currently the most highly cited chemist in the world. For details, refer to <https://www.epfl.ch/labs/lpi/graetzel/>



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