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Hydrogen Valley in the Province of Mantova



Hymantovalley

STATE OF THE ART REVIEW

Scientific literature on LCA and S-LCA studies



UNIMORE
UNIVERSITÀ DEGLI STUDI DI
MODENA E REGGIO EMILIA

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A. INTRODUCTION

Our society and present-day industrial system largely rely upon electricity, which is used to generate light, to power manufacturing plants as well as electronic devices and household appliances, and ultimately to heat and cool residential buildings and commercial properties. Electricity consumption is deemed to increase in the coming years, largely propelled by rising standards of living, flourishing economy and growing population worldwide [1].

Electrification is also seen as an important strategy to reach carbon neutrality and decarbonise energy supply chains [2]. Following onto the Paris Agreement, economies around the world are striving for reducing greenhouse gas (GHG) emissions, which are generally acknowledged as the main cause of climate change. This is expected to increase the pressure on the power grid. For example, the European Union (EU) has recently approved the Revised Energy Performance of Buildings Directive, which, among other substantial changes, includes a gradual phase-out of boilers powered by fossil fuels and a progressive roll-out of recharging points for electric vehicles to replace internal combustion engine cars [3].

An additional load on the power grid is associated with the diffusion of generative artificial intelligence (AI) and blockchain-operated crypto-applications (bitcoin, for example) [4]. To clarify, a generative AI system is estimated to use up to 33 times more energy than a server running conventional task-specific software [5,6]. Meanwhile, in 2022 it was estimated that the total global electricity usage for crypto-assets ranged between 120 and 240 billion kWh per year, thus surpassing the total annual electricity usage of many countries, such as Argentina or Australia [7].

Whilst the increasing need for electricity is becoming more and more challenging, hydrogen is expected to play a pivotal role in the revision of the power grid. As illustrated in Figure 1, hydrogen is the lightest chemical element known, having atomic number 1. At standard conditions, hydrogen is a gas of diatomic molecules having formula H_2 . Hydrogen constitutes around 75% of all normal matter, and stars, including the Sun, are mostly made of hydrogen in a plasma state. Hydrogen is also common on Earth, where it is found in water, organic compounds, and other molecular forms. Nonetheless, pure hydrogen is relatively rare [8].

Historically, hydrogen has been used in various (prominently non-energy related) industrial applications. Nearly 95% of the global production of hydrogen is presently devoted to oil refining, to the chemical industry of ammonia and fertilisers, and to the production of methanol. New use cases are also emerging, such as the replacement of coal for both high temperatures development and chemical reactions in steelmaking [9].

Although the energetic use of hydrogen is still limited, things are due to change soon. Like electricity, hydrogen is an energy carrier and not a primary energy source. The key advantage is that hydrogen is highly flammable, and the reaction with oxygen (combustion) proceeds without producing CO_2 emissions according to the stoichiometric reaction reported in Equation 1:

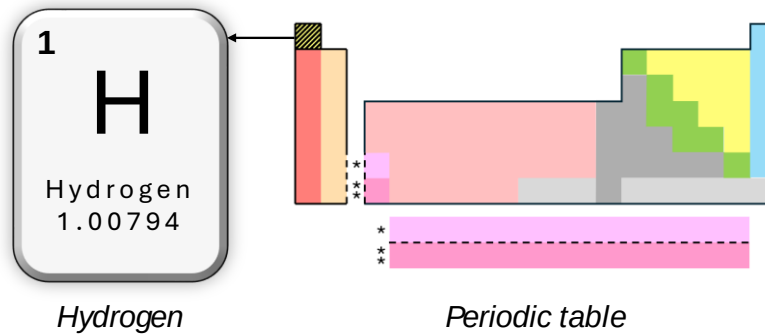
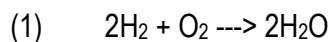


Figure 1 – Hydrogen's properties as chemical element.



The enthalpy of combustion is -286 kJ/mol . Although the stoichiometric reaction in Equation 1 does not release any CO_2 , in practice air is used instead of pure oxygen, and this leads to the emission of NO_x , which are known to form when air is heated to high temperatures [10].

Despite the potential formation of NO_x , hydrogen is generally considered a clean fuel during its use phase, namely at the point of direct combustion or use in fuel cells. Nonetheless, its production and distribution along the entire supply chain do have negative impacts on the environment. Although hydrogen can be produced in different ways, building up and operating the hydrogen generation plant always result in environmental impacts (EIs), regardless of the specific technology in use. As discussed in the following sections, when hydrogen is produced by steam methane reforming (SMR), EIs are mostly due to the plant operations due to the consumption of natural gas as the main feedstock, in addition to power usage. When it comes to electrolysis, the critical factor is the origin of the electricity that is used to power the electrolyser. As a matter of fact, EIs are mainly generated by electricity when the electrolyser is operated through a fossil fuel-dominated grid. These impacts can be minimized when hydrogen is produced with electricity from renewable resources. This is not enough, though, because negative consequences to the environment can still occur when building the hydrogen plant. Moreover, electrolysis consumes water as feedstock, which is also a cause for concern, although often overlooked in the literature [11]. Solar (photovoltaic) power stations and wind farms bring about landscape changes that may cause public resistance [12,13]. Land use may also alter local ecosystems and endanger biodiversity [14].

In order to approach the problem critically, the potential EIs associated with the emerging “hydrogen economy” can be assessed by means of (environmental) life cycle assessment (LCA) [15]. In principle, additional information regarding the consequences on society can be determined through social-life cycle assessment (S-LCA), although this topic is largely under-research in the literature.

(Environmental) LCA is a standardised methodology that reliably and repeatably estimates the effects potentially caused on the environment by a given product, service or organisation along its entire life cycle. Based on inputs (such as feedstock materials and energy) and outputs (such as emissions, products and byproducts),

environmental effects can be evaluated with different impact assessment methods. Historically, CML 2001 and eco-indicator 95 have been very popular for hydrogen-related technologies [8]. However, it is worth mentioning that back in 2011 the EU, through the H2FC-LCA project [16], issued two guidance documents for performing LCA on hydrogen production systems (“HyGuide”) [17] and fuel cells (“FC-HyGuide”) [18]. Both of them comply with ISO 14040 and 14044 standards, as the international references for LCA, and are based on the International Reference Life Cycle Data System (ILCD) coordinated by the Joint Research Centre – Institute for Environment and Sustainability (JRC-IES), through the European Platform on LCA [19].

After a general introduction, the following sections will focus on the available literature pertaining to the LCA of green hydrogen and its supply chain, where “green hydrogen” should be understood in the stricter sense of “hydrogen produced via electrolysis powered with renewables” (including wind, solar, geothermal, hydropower, wave and tidal – but not electricity from biomass). As exemplified in Supplementary information, Table SI.1, reviews dedicated to the LCA of hydrogen (including green hydrogen) are already available in archival papers and open-access materials [8,20–32]. The present contribution builds on these antecedents, while providing an update on the state of the art over the last 5 years, which has witnessed an exponential growth in the field.

A major character of novelty of this survey is the attention being paid to the whole supply chain, which stretches well beyond the sole production of green hydrogen. Further to this, wherever possible the present contribution investigates the potential impact of green hydrogen in its entirety, taking into consideration, for instance, water usage, critical materials depletion, and land occupation in addition to GHG emissions. It is envisaged that this review will thus bring a two-fold benefit to the readership: on the one hand, the overview of LCA methodologies may support those professionals that have been engaged in the LCA of hydrogen; on the other hand, the accurate account of the potential hotspots in the production and delivery of green hydrogen may be an effective aid to researchers, technologists, and policy makers working on decarbonisation strategies.

B. THE COLOURS OF HYDROGEN

Several technologies are currently in use to produce hydrogen at scale, including chemical, biological, electrolytic, and photolytic processes [33]. The choice for a specific technology is a trade-off that takes into account numerous (and often mutually conflicting) variables such as availability of feedstock materials, technology readiness level, market needs, existing laws and policies, as well as funding opportunities and incentives.

A fundamental distinction can be drawn between technologies that are based on fossil fuels, such as natural gas and coal, and those that are based instead on renewable resources, such as biomass [34]. Carbonaceous feedstocks can be converted to hydrogen by reforming or gasification processes. As mentioned above, water

can also be used as the feedstock for producing hydrogen. Although alternative routes are possible, such as water-splitting through thermochemical cycles [35], electrolysis is the most widespread hydrogen production technology starting from water. In this case, it is important to separate hydrogen production plants where the electricity needed for operating the electrolyser comes from renewable resources, such as solar, wind, and hydropower, as opposed to plants where power comes from non-renewable resources such as coal or fossil fuels.

Although this convention has not been standardised, hydrogen produced with different methods is commonly described with different colours [36]. Intuitively, the darker the colour, the worse the EI caused by that hydrogen production method. In this context, the EI is commonly expressed in terms of greenhouse gas (GHG) emissions or global warming potential (GWP). For example, the main output of steam reforming from natural gas is hydrogen, but CO₂ is also generated as an emission. Hydrogen produced via SMR is thus defined as “grey hydrogen” (or, sometimes, “brown hydrogen” [37]). However, if carbon capture and storage (CCS) technology is used to trap and store this CO₂, “blue hydrogen” is obtained instead. “Green hydrogen” is produced from water with renewable energy-powered electrolysis systems, which virtually lead to zero emissions. The lightest shade is “white hydrogen”, which is naturally occurring hydrogen requiring no processing at all. A summary of common “hydrogen colours”, with a brief explanation of the corresponding production technologies [38], is provided in Figure 2.

It is estimated that 48% of hydrogen is currently obtained via SMR [37]. Although the EI of SMR may largely vary depending on the processing conditions such as the reforming temperature and pressure, blue hydrogen is usually regarded as a more sustainable alternative to grey hydrogen owing to the lower overall GHG emissions. However, as previously discussed by Hermesmann and Müller [39], various comparative studies suggest that blue hydrogen performs better than grey hydrogen only in terms of GWP, whereas all other impact categories are negatively affected by the additional material and energy requirements of the CCS technology [40–42]. This ultimately implies that, if multiple impact categories are accounted for, and the evaluation of environmental sustainability is not narrowed down to GWP as the sole indicator, blue hydrogen is not as competitive as expected.

The colour-based terminology may be ambiguous having different meanings in different countries and in different contexts. Green hydrogen is exemplar of this uncertainty. The Green Hydrogen Organisation, which issued the “Green hydrogen standard” in May 2022, defines “green hydrogen” as “hydrogen produced through the electrolysis of water with 100% or near 100% renewable energy with close to zero greenhouse gas emissions (≤ 1 kg CO₂ eq per kg H₂ taken as an average over a 12-month period)” [43]. Nonetheless, the label “green hydrogen” may also be applied to hydrogen produced from sustainable biomass [44]. In order to obviate this ambiguity in hydrogen-related literature (both scientific and technic), intensity of CO₂ emissions and the corresponding GWP have been suggested as a potential classification parameter based on a quantitative

assessment [45]. However, it is worth noting that, in spite of being less ambiguous than colour shades, CO₂ (equivalent) emissions are just a single indicator, and only provide a partial representation of the potential impact of the hydrogen industry on the environment.

Hydrogen colours

-  White hydrogen is geological hydrogen naturally occurring in underground deposits and created through fracking. Presently, there are no strategies to exploit this hydrogen.
-  Green hydrogen (renewable hydrogen) is made by using electricity from renewable sources to electrolyse water and emitting zero CO₂. Green hydrogen currently makes up a small percentage of the overall hydrogen, because production is expensive.
-  Yellow hydrogen is made through electrolysis using solar power.
-  Pink (or purple, or red) hydrogen is generated through electrolysis powered by nuclear energy.
-  Grey hydrogen is the output of steam reforming from natural gas. This is the most common form of hydrogen.
-  Blue hydrogen is the output of steam reforming from natural gas when carbon capture and storage (CCS) technology is used to trap and store the CO₂, being generated as byproduct.
-  Black and brown hydrogen are produced using black coal or lignite (brown coal) in the hydrogen-making process. These are the most environmentally damaging variants in the spectrum.
-  Turquoise hydrogen is made using a process called methane pyrolysis to produce hydrogen and solid carbon. Its production has yet to be proven at scale.

Figure 2 – Common colour-based nomenclature applied to hydrogen produced by different methods.

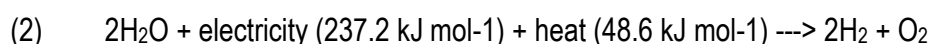
C. ELECTROLYSIS PATHWAYS

Although electrolysis is a well-established industrial process, only a minor fraction of hydrogen (around 4%) is produced from water due to its relatively high processing cost [45]. Conceivably, the percentage of “truly” green hydrogen (namely, coupling water electrolysis and renewables) is even smaller.

This situation is due to change in the near future, though, because public investment and climate policies worldwide push for “greener” options. For example, the REPowerEU plan (introduced in the EU in May 2022) requires that 45% of energy in the EU will come from renewable sources by 2030. The increased availability of

renewable electricity, which will likely be accompanied by a significant reduction in costs, is expected to favour the growth of green hydrogen over other hydrogen technologies [24,45]. Meanwhile, green hydrogen can be easily stored, thus serving as an energy reservoir for the excess of wind, solar, and hydro-power, and other renewables that cannot be generated in a consistent fashion due to the dependence on hourly, seasonal or weather-related variables [46–49]. This approach to storing energy is generally known as “power-to-gas” [50]. However, even though the increasing share of renewables and the deployment of green hydrogen at scale may appear to proceed hand-in-glove, it is important to recognise that the production of green hydrogen can also compete with existing decarbonisation targets by diverging renewable electricity from the grid [48,51]. Otherwise, scaling up the production of green hydrogen may require the massive deployment of new renewable electricity capacity in addition to the existing one according to the “additionality principle” [52].

The starting point for electrolysis is water (or steam), which must be preliminarily purified to avoid mineral deposition and uncontrolled reactions in the electrolytic cell. Electrolysis consists in splitting water molecules to hydrogen (gas) and oxygen (gas) through the direct application of electricity according to Equation 2 [53]:



Oftentimes, the required heat is also provided by electricity. It can be estimated that 55 kWh of electricity in total are necessary for water splitting at an efficiency of 60% [34].

There exist different kinds of electrolysis cells. The following sections summarise the main features of commercially available technologies. For illustrative purposes, Figure 3 shows the functioning mechanism of an alkaline electrolytic cell. Regardless of the specificities of the individual technologies, basically all electrolysis cells are comprised of four main components, namely the electrodes, including (i) the oxygen electrode (anode) where oxygen evolution reaction occurs and (ii) the hydrogen electrode (cathode) where the hydrogen evolution reaction occurs; (ii) an electrolyte that enables ionic conductivity (ion transfer), and (iv) a separator, which is a thin material layer that is ion-conductive, but gas-impermeable [26].

During electrolysis, a direct current voltage is applied to the electrodes, and water is consistently supplied to the cell. As a result, redox reactions take place, and water molecules are split to oxygen and hydrogen gases according to Equation 2. While the separator allows ions and electrons to pass through, gas permeation is impeded, and this hinders the recombination of hydrogen and oxygen back to water [26].

Electrolytic cells can be assembled in series to build up a “stack”. Neighbouring cells are separated by a bipolar plate called “interconnect”, and the stack is completed by an appropriate framing [54]. The electrolyser is ultimately a collection of multiple stacks. Besides the cells, other components are needed for the electrolyser to function as intended [26]. These include balance of plant (BoP) components and power electronics (PE) that are necessary for pumping water into the stack, purifying the gasses, and managing the electricity that is required for water splitting [54,55].

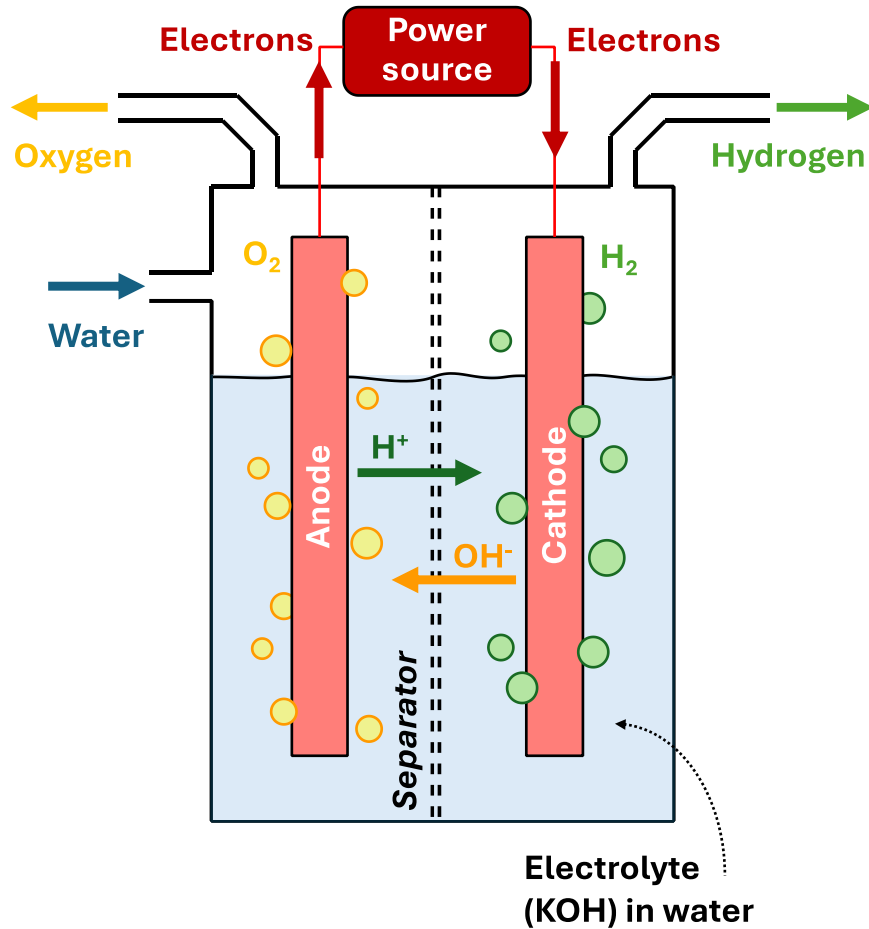


Figure 3 – Schematic of an electrolysis cell.

The hydrogen developed through the reaction in Equation 2 at the cathode of each cell is collected, cooled, purified, compressed and stored. Some electrolyzers can generate hydrogen at high pressure, which avoids the compression stage. Water splitting also generates oxygen, which can be similarly collected for industrial use, or simply released to the atmosphere. In practical terms, this is still a matter of debate. The recovery of oxygen offers potential benefits because oxygen is the second-most used industrial gas after nitrogen, with applications ranging from the metal sector to various chemical processes [39,56]. In the multi-unit reactor configuration for catalytic methanation of flue gases described by Chirone et al. [57], for example, an electrolyser is exploited for producing both hydrogen and oxygen. Hydrogen is used for the purification and methanation of CO₂, and oxygen for the combustion of methane that sustains the calcination reaction needed to regenerate the CaO used in the carbonator reactor.

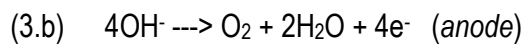
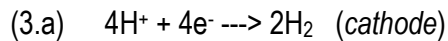
In spite of these potential benefits enabled by oxygen recovery, if green hydrogen was deployed at scale, this would oversaturate the oxygen market. As a term of comparison, according to the numbers reported by de Kleijne et al. [52], the estimated European oxygen market for 2030 would be around 17 million tonnes per year, while the volume of oxygen co-produced in electrolytic processes would grow to 80 million tonnes per year by

that time, owing to the European target of producing 10 million tonnes of green hydrogen per year by 2030. This justifies the frequent assumption that oxygen is simply vented to the air.

Currently, although the technology readiness level (TRL) is different, there are three main types of electrolyzers that have been translated “from lab to fab”, namely alkaline electrolyzers, polymer electrolyte membrane (PEM) electrolyzers, and solid oxide electrolyzers [25].

C.1. ALKALINE ELECTROLYSERS

In alkaline electrolyzers, pure water is preliminarily converted to a highly concentrated aqueous solution of an alkaline electrolyte (typically, KOH or, more rarely, NaOH or NaCl). Under a direct current, hydrogen evolves from the cathode according to Equation 3.a, whilst hydroxide anions migrate across the separator (or diaphragm) to the anode, where they recombine to oxygen and water according to Equation 3.b.



The anode is usually made of nickel or nickel-coated steel, while the cathode is made of steel, whose surface is activated by a catalyst coating.

The separator plays a pivotal role in this set-up, as it must be permeable to water ions and impermeable to gases simultaneously. In the past, the separator was routinely made of a thick asbestos layer, but the associated health hazards and technical constraints (with the operating temperature being limited to 80 °C) have prompted research in safer and more performing alternatives such as ion exchange inorganic membranes.

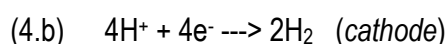
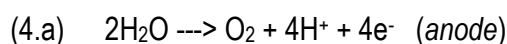
Atmospheric alkaline electrolyzers can generate hydrogen with a pressure between 1 and 6 bar, while high pressure electrolyzers generally work between 6 and 30 bar, although higher pressures have been demonstrated at laboratory scale [58]. High pressure electrolyzers bypass the post-production compression step, and therefore avoid the associated costs and EIs. However, as a drawback, the combined effect of high pressure and high temperature compromises the separator’s impermeability to gases, hence leading to lower purity hydrogen.

Alkaline electrolysis is a mature and relatively affordable technology, whose investment cost being nearly proportional to the installed capacity and, ultimately, to the total surface area of the electrolyser. As a result, alkaline electrolysis is the most widespread hydrogen production technology at commercial level worldwide [8,54].

C.2. POLYMER ELECTROLYTE MEMBRANE (PEM) ELECTROLYSERS

Polymer electrolyte membrane (PEM) electrolysis is also known as “proton exchange membrane” (PEM, as before) electrolysis or “solid polymer electrolyte” (SPE) electrolysis.

Like alkaline electrolyzers, PEM electrolyzers are a low-temperature technology working at approximately 50 °C -100 °C. However, PEM electrolyzers use a polymer electrolyte membrane instead of a liquid electrolyte. At the anode, water is oxidized producing oxygen (gas), electrons, and protons (H⁺) as indicated in Equation 4.a. Protons move through the membrane to reach the cathode, where they are reduced closing the circuit and generating hydrogen (gas) according to Equation 4.b.



The unit consisting of the anode, the cathode, and the membrane is known as “membrane electrode assembly” (MEA). The thick separator typical of alkaline electrolyzers (thickness: around 5 mm) is replaced here by a very thin gas-tight polymer membrane, such as Nafion (thickness: around 0.2 mm). The electrodes are thick-coated with noble metals, such as platinum or iridium [59].

The hydrogen purity is typically very high, exceeding 99.99 vol.% even without any auxiliary purification equipment. Another advantage is that PEM electrolyzers can work under a variable power supply. This happens because (unlike ionic transportation in alkaline electrolyzers) proton circulation in PEM electrolyzers adapts quickly to power fluctuations [8].

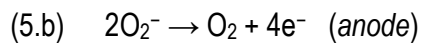
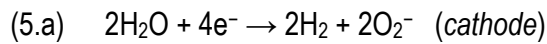
PEM electrolyzers have a higher power density than alkaline electrolyzers. However, they are commercially available only for low-scale production. Moreover, noble metal electrodes and proton membranes still need substantial investment capitals [8,54].

An emerging technology combines a PEM electrolyser with a PEM fuel cell, which is an electrochemical device that converts the chemical energy of hydrogen back into electrical energy. The large-scale version of this technology, the so-called discrete regenerative fuel cell (DRFC), makes it possible to store the excess energy intermittently produced by fluctuating renewable sources like wind and solar by generating and storing hydrogen using the electrolysis device, and to give back power from hydrogen using the integrated fuel cell when required. The small-scale version of this technology, which is known as unitised regenerative proton exchange membrane fuel cell (UR-PEMFC) or unitised regenerative fuel cell (URFC), offers some additional advantages, such as a lower capital cost and a simplified architecture [60].

C.3. SOLID OXIDE ELECTROLYSERS

Solid oxide electrolyzers (frequently abbreviated as SOEs) are an emerging technology enabling the electrolysis of water – or, more exactly, of steam – at high temperature up to 1000 °C. In principle, about 40% of the energy required for steam electrolysis can be supplied as heat, and the electricity demand can be reduced substantially with respect to alkaline electrolysis and PEM [61]. This approach is particularly convenient when a high-temperature heat source is available, for example with nuclear reactors or geothermal energy spots.

In SOEs, steam is fed to the cathode, where water molecules are reduced to develop hydrogen (gas) according to Equation 5.a. Steam can be supplemented with recycled oxygen. The oxide anions produced at the cathode move through the solid electrolyte to the anode, where they react forming oxygen (gas) and closing the circuit according to Equation 5.b.



The cathode is a cermet (i.e., ceramic-metal composite) made of nickel and yttrium-stabilized zirconia (YSZ), the solid electrolyte is made of YSZ, and the anode is made of perovskite. SOEs feature high efficiency for hydrogen production with relatively low electricity consumption, which is conducive to low EIs, especially GHG emissions [62]. However, SOEs are prone to fast degradation, because load changes result in temperature fluctuations that are likely to cause the membrane to crack. The reduced lifetime of SOEs is hampering their wider adoption for commercial use [63].

D. LITERATURE SEARCH: METHODOLOGY

A reference sample of 35 research articles [4,34,39–42,45,46,48,51,52,54,55,57,62,64–83] was obtained from a search in Scopus for the environmental LCA of the supply chain of green hydrogen, namely hydrogen produced from electrolysis powered by renewable energy. In this regard, it should be mentioned that, being a low emitting technology, nuclear power can also be used to conveniently produce low-carbon electrolytic hydrogen [84]. However, nuclear plants rely on a finite supply of radioactive materials, mainly uranium. For this reason, nuclear power was excluded from the “renewables” in the present survey.

The analysis of the literature was focused on contributions published from 2019 onwards to provide an up-to-date view of the field. All papers were scrutinised in order to respond fundamental questions regarding the supply chain of green hydrogen and the determination of its potential EIs, while also capturing the main features of the applied LCA methodologies. Emerging applications of green hydrogen were also accounted for. However,

research specifically addressed to the functioning and optimisation of fuel cells was not included, as this was deemed a self-standing technology needing a separate analysis.

The outcome of the literature survey is discussed in the following section. Precise data is provided in the Supplementary information, Table SI.2, which lists for each selected paper: Geographical context, system boundary, functional unit, software, background database, life cycle impact analysis (LCIA) method(s), impact categories or damages calculated, main outcomes, emissions, and methodological notes. Table SI.2 also gathers detailed information about the production (including type of electrolysis and power used), delivery (compression/liquefaction and transportation mode) and application of green hydrogen.

E. LCA AND GREEN HYDROGEN SUPPLY CHAIN: STATE OF THE ART

E.1. TREND OVER TIME

As previously mentioned, the number of studies applying LCA methodologies to the evaluation of the potential environmental burdens tied to the production and supply chain of green hydrogen has increased rapidly over the last 5 years. The trend is apparent in the bar chart in Figure 4 (based on data in Table SI.2), where the number of papers published in 2024 is still provisional and likely due to rise by the end of the year.

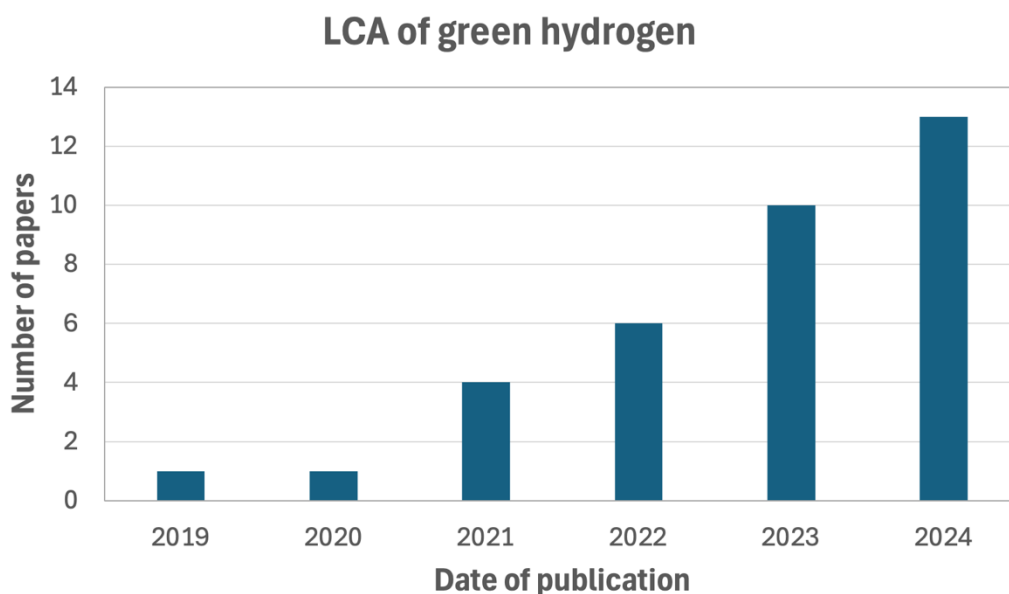


Figure 4 – Time distribution of the selected research papers presenting the LCA of green hydrogen.

With green hydrogen being regarded as a zero-emission energy vector, the strong interest being paid to green hydrogen in the scientific community clearly reflects the push of various governments and state organisations towards the achievement of climate neutrality in the short term. However, as further discussed in the following sections, the perception of green hydrogen as a “zero emission” technology may be misleading when fact-checked in a life-cycle perspective, not to mention its consequences on other impact categories beyond GWP.

E.2. GEOGRAPHICAL CONTEXT

Interestingly, the greatest part of the recent literature examines the deployment of green hydrogen in so-called “developed” countries, especially within the EU, which accounts for 18 papers out of 35 (51%). As shown in Figure 5 (based on data listed in Table SI.2), this number increases further if the United Kingdom (UK) is also counted in, since 3 additional papers cover the EU + UK, and 1 more the UK only.

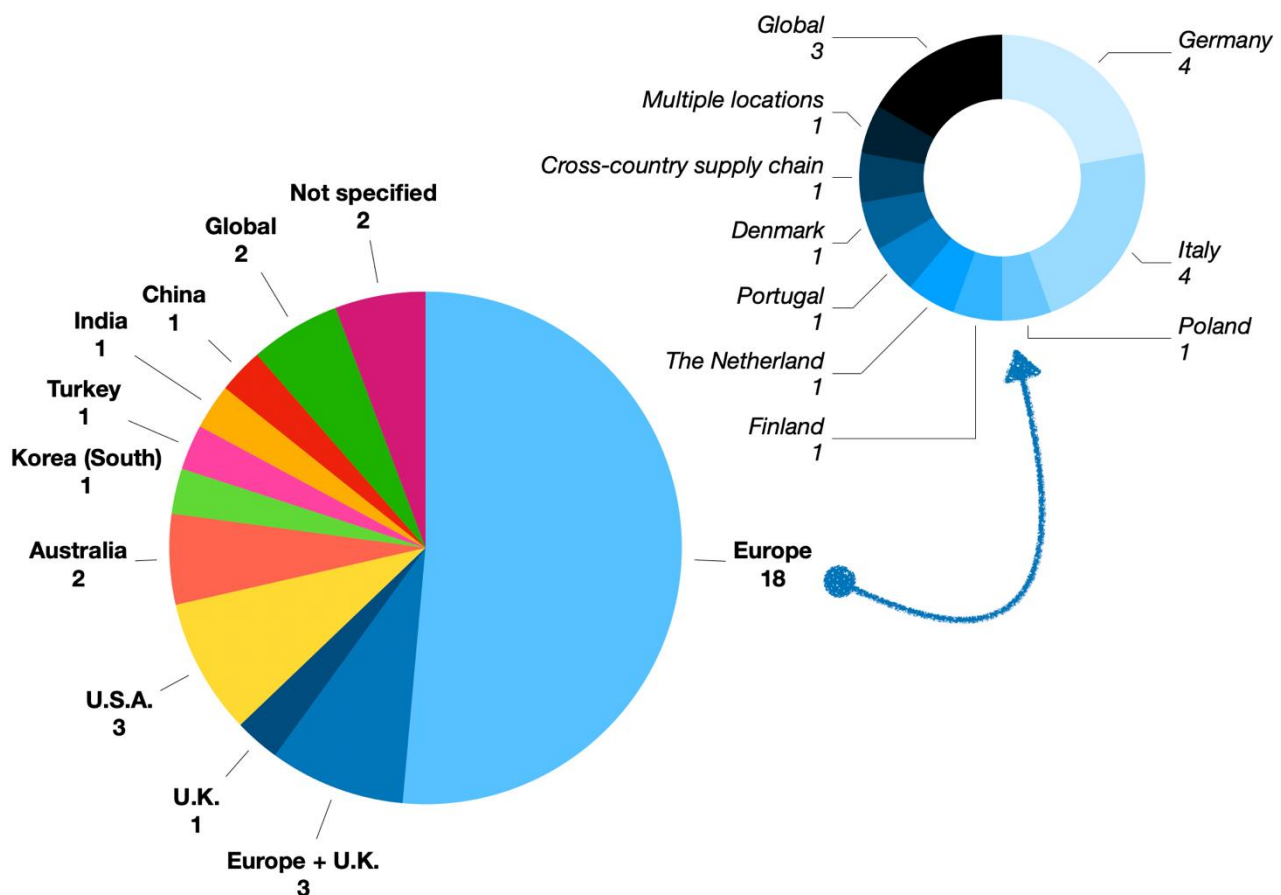


Figure 5 – Geographic context of the selected research papers presenting the LCA of green hydrogen.

In this respect, it is worth noting that the adoption of green hydrogen as energy vector matches very well the ambitious targets of the EU that, with the European Green Deal, aims to become the first climate-neutral

continent [85]. Meanwhile, as a consequence of the war in Ukraine, the European Commission is implementing the REPowerEU Plan to overcome its dependence on Russian fossil fuel imports [86]. Besides saving energy, the main goals of the REPowerEU Plan consist in diversifying the energy sources for the EU and incentivising the production of clean energy. Presently, various countries within the EU rank amongst the main producers of solar, wind, geothermal and hydropower, as presented in Figure 6 based on IRENA data for 2022 [87].

The latest available statistics (December 2023 for year 2022) show that the share of EU gross final energy consumption from renewable sources in 2022 was 23.0 %, which was around 1.1 percentage points higher than in 2021 [88]. Although promising, this value is still far from the 42.5% share targeted for 2030, with the idea of increasing it further to 45%. The production of green energy is thus predicted to grow rapidly in the near future, and this will likely promote a more competitive and widespread green hydrogen economy in the EU.

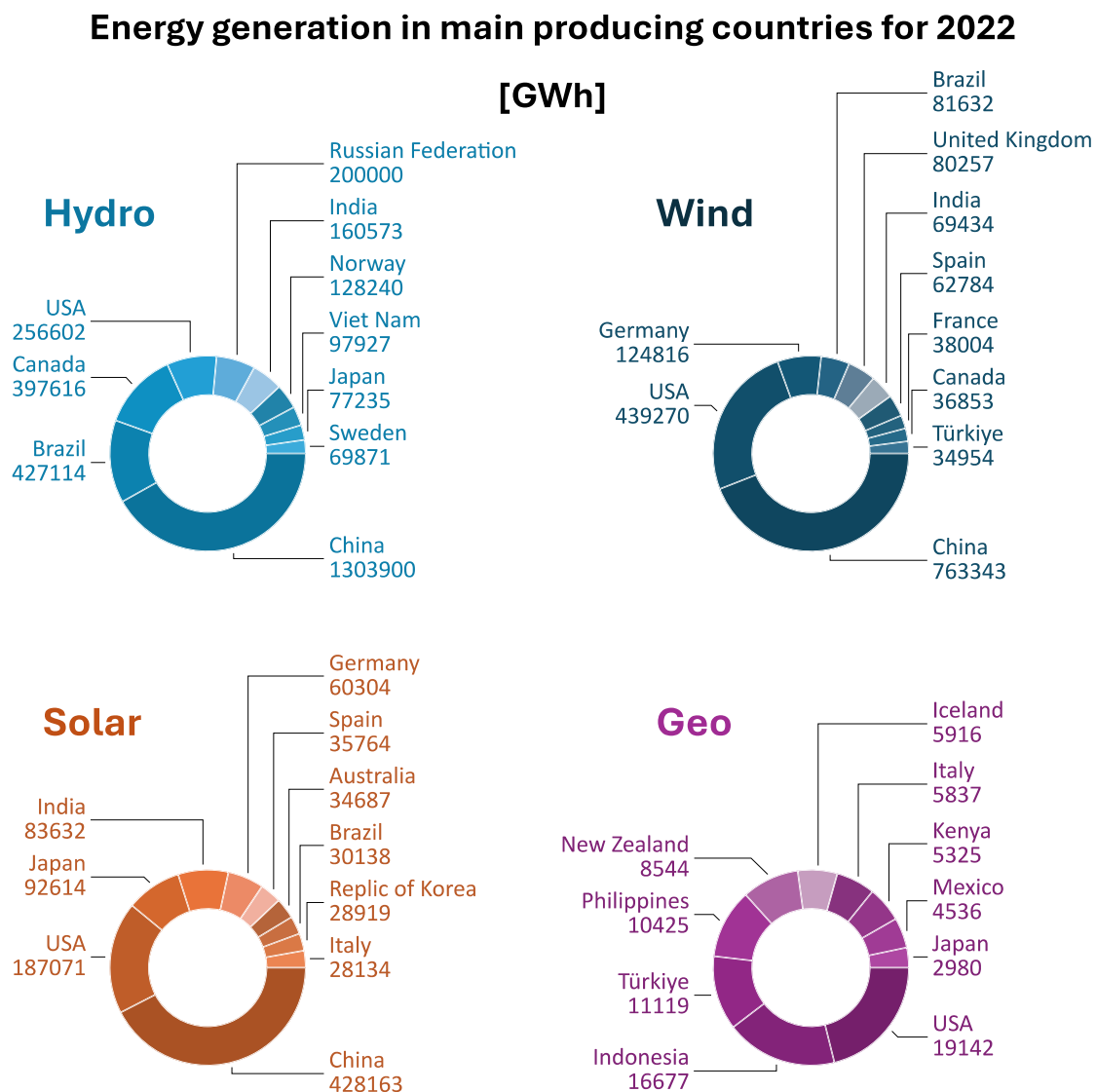


Figure 6 – Top-ten country rankings based on their annual electricity generation (expressed in GWh) for different kinds of renewables. Values refer to year 2022. Data extracted from IRENA database [87].

The United States of America (USA) make for another 9% of the reviewed papers (3/35). Achieving climate neutrality is still a controversial topic in the USA. Historically, the opposition of the Republican party has led American presidents to join, exit and then re-enter the Paris Agreement. Eventually, on Earth Day 2021 the USA pledged to reduce GHG emissions to 50-52% below 2005 levels by 2030. Meanwhile, wind and solar energies have been growing rapidly, doubling in just five years to represent 12% of the grid in 2020 [89].

South Korea (officially, the Republic of Korea) and Australia have identified the establishment of a shared green hydrogen market as a crucial opportunity for their economies. On the one hand, South Korea is the main producer worldwide of fuel cell technology, but it largely relies on imports to satisfy its energetic needs. On the other hand, owing to its massive capacity to produce electricity from renewable resources, Australia is set to become one of the top exporters of green hydrogen by 2030 [90].

Although its role is not obvious from the data in Table SI.2, and the graphs in Figure 5, it is worth mentioning that China is presently the world leader for the generation of electricity from renewable sources including wind, solar and hydropower, as shown in Figure 6. The relatively small number of papers published in China about the LCA of green hydrogen may thus reflect a diversification of the strategies pursued in the country to reach carbon neutrality by 2060 [91].

In more pragmatical terms, it is also worth noting that water electrolysis is still a very expensive technology. In addition to the high cost of renewable energy, the wider uptake of green hydrogen is affected by the substantial up-front investment cost of the electrolyser. This financial hurdle is aggravated by the relatively low yield of electrolyzers. Presently, forecasts for alkaline electrolyser installed costs in 2050 vary largely from USD 100 per kW up to USD 1,200 per kW depending on the underpinning assumptions [92]. Ultimately, this means that building a green hydrogen facility working at scale requires hundreds of millions of dollars, which may represent a formidable barrier to the diffusion of green hydrogen in developing countries.

E.3. METHODOLOGICAL CONSIDERATIONS ABOUT LCA

A scrutiny of Table SI.2 immediately reveals that there is a strong variability in methodology when LCA is applied to the supply chain of green hydrogen. A fundamental distinction should be drawn between studies targeting the production (electrolysis), the delivery or the use phase of green hydrogen. Being the goal of the assessment different, the functional unit, the system boundaries and, oftentimes, the LCIA method also change accordingly. As previously mentioned, more than ten years ago the EU issued a guidance document for harmonising the LCA of hydrogen production systems, “HyGuide” [17]. However, looking at Table SI.2, it is possible to observe that, despite the prevalence of European studies, the “HyGuide” directions are largely overlooked in the literature. As a result, there is still a strong methodological variability even if the scope is narrowed down to the LCA of green hydrogen production.

Nearly all the contributions analysing the production of green hydrogen in Table SI.2 define the functional unit as a mass of hydrogen produced, or a volume of hydrogen at a given temperature and pressure. As already observed by Wilkinson et al. [31], this seems to be the most practical choice, also corresponding to the HyGuide directions stating that “For H₂ production systems, the functional unit must be production of a certain amount of hydrogen” [17]. However, while the HyGuide guidelines recommend that the temperature, pressure, purity and production capacity should be clearly stated in the LCA, this information is in fact rarely available.

It is also worth noting from Table SI.2 that most often the system boundaries are defined as “cradle-to-gate”. The transportation and the use phases are only included in those studies that chiefly analyse, respectively, the delivery and the application of green hydrogen. Sometimes, the system boundaries are determined as “well-to-wheel”, when the assessment is focused on the use of green hydrogen as a fuel. The end-of-life stage is rarely seen in the selected research papers with only 4 occurrences, two of which deal with the use of green hydrogen for the production of heat, and thus describe the end-of-life in terms of hydrogen-based heating solutions [69,82]. Ultimately, the disposal or recycling of the electrolyser, which represents the “grave” stage of green energy production via water electrolysis, is only considered in two papers out of 35, one by Gerloff et al. [70] and one by Khan et al. [72].

As for the LCIA, the most widespread methodology in the selected papers is ReCiPe midpoint (frequently, hierarchical), which occurs in at least 14 contributions out of 35. One of the main strengths of this methodology is the wide range of impact categories that provide a comprehensive understanding of the EIs. These midpoint values can also be treated to determine normalised damage categories as endpoint results [93]. The ILCD method (2 papers) and the Environmental footprint framework that replaced it (7 papers) are also quite common in the literature. CML is only applied in 4 papers, which is surprising given that CML is the most frequently used (non-GWP) LCIA method in the hydrogen production LCAs reviewed by Wilkinson et al. [31]. This discrepancy may be due to the different topics under examination, since the survey conducted by Wilkinson et al. [31] considers all hydrogen production technologies, and not specifically green hydrogen. Moreover, the paper by Wilkinson et al. [31], which dates back to 2023, mainly describes the state of the art up to 2022, with the only exception being a paper by Weidner et al. [81] that was published in 2023, but had already become available online in December 2022. The HyGuide document [17] also favoured CLM over other LCIA method, since it recommended the LCA practitioner to “Select the relevant environmental impact categories from the ILCD Handbook “Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment” (which was still in draft version at the time) and to “Use the CML impact methods (CML 2011) if no other method is considered more appropriate”. However, it is worth noting again that HyGuide was published in 2011. Since then, changes have been made to LCIA methods; for example, ReCiPe was updated in 2016 [94]. Even before recommending CML, HyGuide acknowledges that the scientific robustness (including the level of uncertainty), the application in LCA practice, the development that has occurred over time, and the

European environmental policy goals are the primary criteria for selecting the LCIA method(s). As detailed in the following sections, Weidner et al. [81] and Weidner and Guillén-Gosálbez [82] applied special characterisation factors related to the planetary boundary categories that make it possible to calculate the impact values in each category and compare them to the allocated safe operating space of the planetary boundaries. Finally, Figure 7 summarises the distribution of the 35 reviewed papers based on the publication journal (details in Table SI.2).

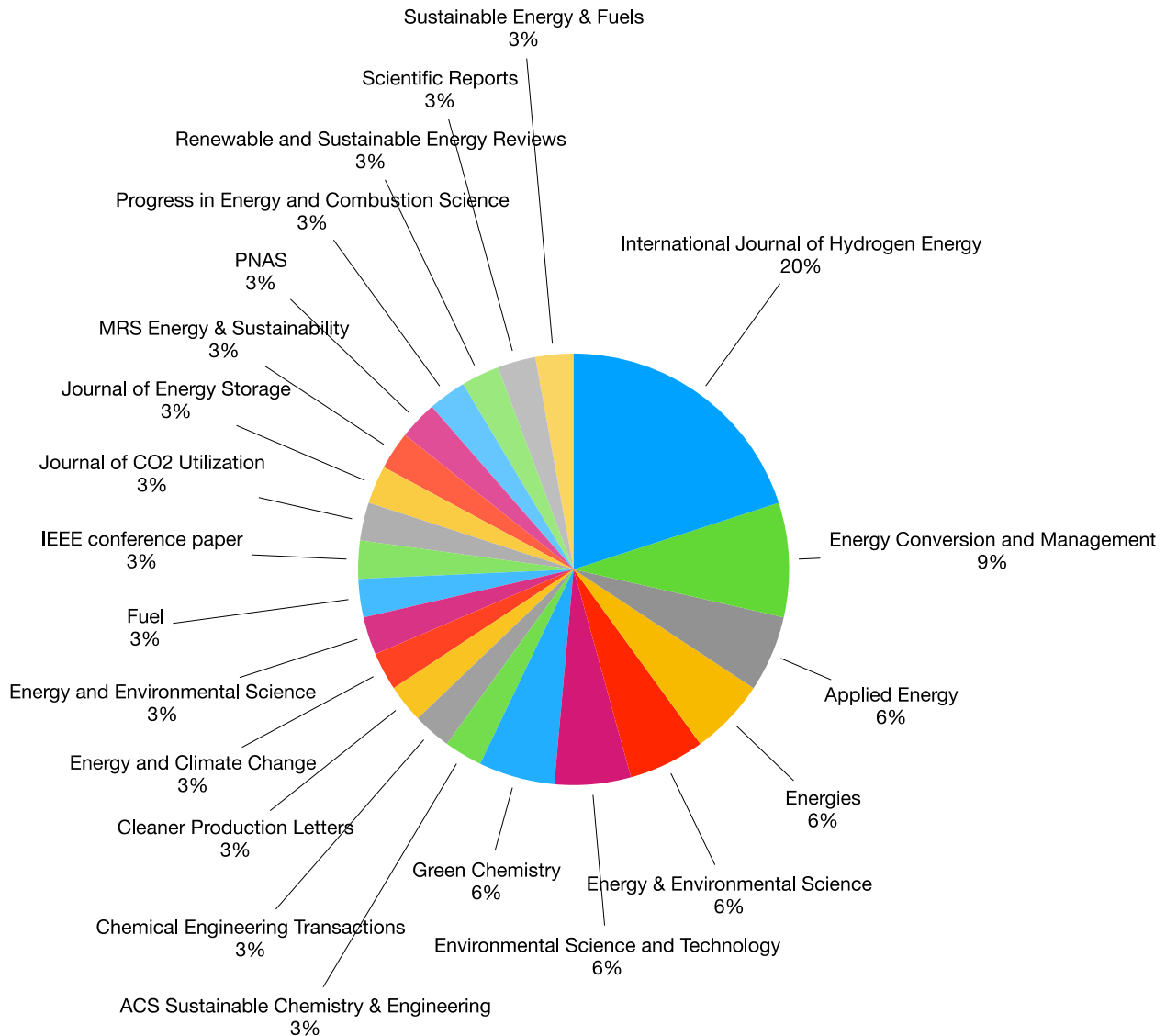


Figure 7 – Publication journals of the 35 reviewed papers.

Consistently with the observation of Chelvam et al. [20], the greatest part of the literature has been published in the International Journal of Hydrogen Energy, accounting for 20% of the selected contributions (7 papers out of 35). Owing to the prospective role of green hydrogen as a low-carbon energy vector, other popular journals are Energy Conversion and Management (3 papers), Applied Energy (2 papers), Energies (2 papers), Energy &

Environmental Science (2 papers), Environmental Science and Technology (2 papers). Green Chemistry also accounts for 2 papers. Just a minor number of papers has been published in more generalist journals, with one paper dealing with the green hydrogen-crypto economy duo in PNAS [4] and one paper analysing the supply chain of heat pumps in Scientific Reports [77].

F. GREEN HYDROGEN PRODUCTION

The graph in Figure 8 (based on Table SI.2) demonstrates that the three main electrolysis technologies – alkaline, PEM and solid oxide – are all represented in the selected literature regarding the LCA of green hydrogen. The total number of case studies in Figure 8 appears to be higher than 35 because several papers comparatively assess two or more electrolysis technologies simultaneously.

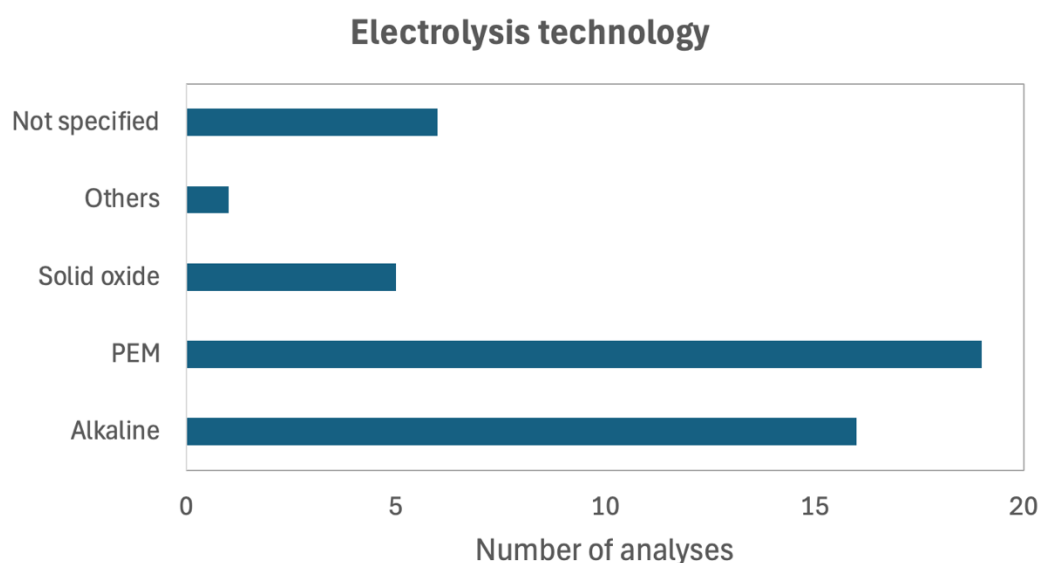


Figure 8 – Number of analyses conducted in the selected papers for each kind of electrolysis technology.

Reasonably, the most common technologies are alkaline electrolysis (16 LCA studies) and PEM electrolysis (19 LCA studies), because they presently feature the highest TRLs, namely 9 for alkaline electrolysis and 6-8 for PEM, according to Wilkinson et al. [31]. The TRL of solid oxide electrolysis is relatively lower, around 5 [31], which justifies the limited occurrence of this technology in the literature. Only one paper [45] analysed the EI of green hydrogen produced by anion exchange membrane electrolysis, which is still an emerging technology at a very low TRL of 2-3 [31].

Patel et al. [75] systematically analysed the potential climate change caused by several hydrogen production methods. The comparison took into consideration grey hydrogen, blue hydrogen, turquoise hydrogen (thermal

decomposition of methane, TDM), and green hydrogen (PEM electrolysis). Turquoise hydrogen, in spite of being produced by the pyrolysis of methane, has recently attracted attention in the literature as a low-energy-intensity alternative to green hydrogen [95]. For methane-based technologies (grey, blue and turquoise hydrogen), two different supply chains for the delivery of methane to Finland were also modelled in the contribution by Patel et al. [75], namely the liquefied natural gas (LNG) route from the U.S.A., and the transmission pipeline for methane in the gaseous form from Russia. As summarised in Table 1, the emissions associated with green hydrogen were the lowest, with values comprised between 0.6 kg CO₂ eq./kg H₂ when relying upon wind energy and 2.5 kg CO₂ eq./kg H₂ when using solar energy. All methane-based production methods resulted in higher emissions than green hydrogen, although the results for grey, blue, and turquoise hydrogen were different for the LNG route and the pipeline route, with the LNG route consistently leading to higher emissions. As expected, with the analysis being focused on carbon emissions, blue hydrogen performed better than grey hydrogen thanks to the CCS technology. Among all methane-derived hydrogen forms, pipeline turquoise hydrogen performed the best, because the production of solid carbon instead of CO₂ in the reactor largely compensated for the emissions caused by burning natural gas in the combustion chamber. On average, the emissions calculated by Patel et al. [75] for methane-derived hydrogen were worse than previous literature data because the LCA included the extraction and transportation emissions of methane. A more detailed summary of emissions associated with the production, delivery and application of green hydrogen is included in the Supplementary information, Table SI.2. However. In this regard it is worth noting that the GWP values available in the literature vary largely across different studies depending on the functional unit and system boundaries adopted in the LCA, on the inventory data, as well on the LCIA method adopted [32,96]

Table 1 – GWP (over 100 years, GWP-100) associated with hydrogen production methods (for grey, blue, and turquoise hydrogen: methane supplied in either liquid or gaseous form; for green hydrogen: electrolysis powered by wind energy, solar energy, or a mix). Data from the LCA conducted by Patel et al. [75].

GWP-100 [kg CO ₂ eq./kg H ₂]					
<i>Origin</i>	<i>Liquified methane</i>	<i>Gaseous methane</i>	<i>Wind energy</i>	<i>Solar energy</i>	<i>Wind-solar mix</i>
Grey	13.9	12.3	--	--	--
Blue	9.3	7.6	--	--	--
Turquoise	8.3	6.1	--	--	--
Green	--	--	0.6	2.5	1.6

For solar-powered green hydrogen, Mio et al. [42] compared the three main electrolysis types, namely alkaline, PEM, and solid oxide. The LCA accounted for 18 different impact categories as defined by the ReCiPe Midpoint H method. Notably, PEM electrolysis performed poorly on 16 categories out of 18 due to the noble metals used

to fabricate the electrodes and due to the substantial electricity needed. Although solid oxide electrolysis performed better than alkaline electrolysis in most impact categories, GWP was much worse due to the natural gas used for heat generation. Since green hydrogen is generally sought after as a key enabler of decarbonisation, alkaline electrolysis was finally identified as the least impactful production pathway for green hydrogen [42].

Zhao et al. [54] systematically compared the EIs potentially caused by the three main electrolysis technologies with a focus on the electrolyser. Assuming the same functional unit corresponding to 1 m² of the electrolysis cell (including both active and non-active surface), the GWP caused by the PEM stack largely exceeded those of the solid oxide stack (16 times) and the alkaline stack (9 times). Similarly, the mineral resource scarcity attributable to the PEM electrolyser was much higher than those associated with the solid oxide stack (71 times) and the alkaline stack (20 times). The environmental performance of the PEM stack was primarily compromised by the platinum group metals being used in the electrodes (especially the oxygen electrode) and in protective coatings on the interconnects. Furthermore, toxicity-related impacts to both human health and ecosystem resulted to be very high for all stacks [54].

GWP and other impact categories tied to electrolytic hydrogen are strongly sensitive to the nature of the electricity being used in the electrolyser [55,62]. The report issued in the framework of the New Energy Externalities Development for Sustainability (NEEDS) project in 2008 [97] showed that the emissions associated with electrolytic hydrogen can be reduced by about 90% if the required electricity is supplied by renewable resources instead of a fossil fuel-based grid. A similar trend was also observed by Gerloff [70], who reported a progressive reduction in GWP as a result of the increasing adoption of renewables for all the electrolysis technologies, including alkaline, PEM and solid oxide. However, Gerloff [70] also pointed out that a definitive ranking based on GWP is not feasible, because the predicted emissions for each electrolysis technology largely depend on the electricity scenario adopted. For example, for the energy scenario representing the German grid in 2019, PEM technology would produce the highest emissions, and solid oxide electrolysis the lowest. However, if a complete shift to renewables was accomplished, solid oxide electrolysis would lead to the highest emissions due to its substantial heat demand, while the least emitting technology would be alkaline electrolysis [70].

Since the electricity need to power the electrolyser for the production of “fully” green hydrogen entirely relies on renewables, the EIs of green hydrogen are largely affected by climate and geographic variations, as they govern the availability of wind and solar [4,98]. Integrating offshore wind farms and floating photovoltaic infrastructure can partly obviate this obstacle, as solar irradiance and wind speed are correlated negatively, thus leading to a more consistent production of electricity [99]. Although less common than other renewables, geothermal power has also been considered for powering the production of green hydrogen because it is not an intermittent renewable resource. However, geothermal power also comes with some drawbacks. In particular, the well productivity might decline over time, and digging new wells might become necessary to drive the geothermal

power plant [68]. Moreover, gases such as CO₂ and H₂S may be dissolved in the geothermal fluids, and finally released to the atmosphere. This calls for the implementation of dedicated capture and storage technologies [100]. Notably, green hydrogen produced with hydropower is largely under-represented in the recent literature. This point may deserve further attention given the supremacy of hydropower over all other renewables, as shown in Figure 6.

If different renewable sources for electricity are compared, based on the literature review conducted by Bhandari et al. [8], wind-powered electrolysis ranks the best in terms of GWP, followed by hydro-powered electrolysis. There is not a consensus in this regard, though. For example, according to the Hydrogen Council [101], the emissions associated with wind-powered electrolysis would be half of those associated with solar power, but electrolysis with run-of-river hydropower could achieve even lower emissions than wind-powered electrolysis. Conversely, it is generally acknowledged that the environmental performance of solar-powered electrolysis is comparatively low [52], because it is blemished by the energy-intensive nature of photovoltaic cells and by the use of hazardous compounds such as acids and hydroxides to produce them [72]. As a result, the environmental burden of solar-powered electrolysis is presently the highest, and largely exceeds those of wind- and hydro-powered electrolysis, regardless of the specific electrolyser in use [48]. However, this ranking may change when additional impact categories, and not just climate change, are accounted for, as demonstrated by Gerloff [48]. Moreover, the prospective LCA published by Weidner et al. [81] shows that green hydrogen produced with solar power will attain a lower carbon footprint with the progressive decarbonization of the grid, because this will reduce the carbon intensity of the photovoltaic cells. This result challenges the common understanding that the future deployment of a green hydrogen economy should rely upon wind-powered green hydrogen as a less emitting technology than solar-powered green hydrogen.

In practice, electrolysers have limited operational flexibility, and the intermittency of the power source decreases the lifespan of the electrolyser [62]. Consequently, intermittent electricity sourced from renewables may need to be supplemented with back-up electricity from the grid in order to ensure continuous operation of the electrolyser. However, this is likely to worsen the carbon intensity of green hydrogen depending on the specific composition of the grid mix [39,55,62,74,79].

In this regard, it is worth mentioning that the grid composition varies strongly across different countries. For example, Figure 9, which is based on data from the International Energy Agency, IEA [102], shows the power supply breakdown for some selected countries in 2022 (except for China, whose data refer to 2021). The total energy supply accounts for all the energy produced in or imported to a country, minus the energy exported or stored. Basically, it represents all the energy required to supply end users in the country, including direct use and transformation into fuels or electricity [102]. The grid mix is obviously different in different countries.

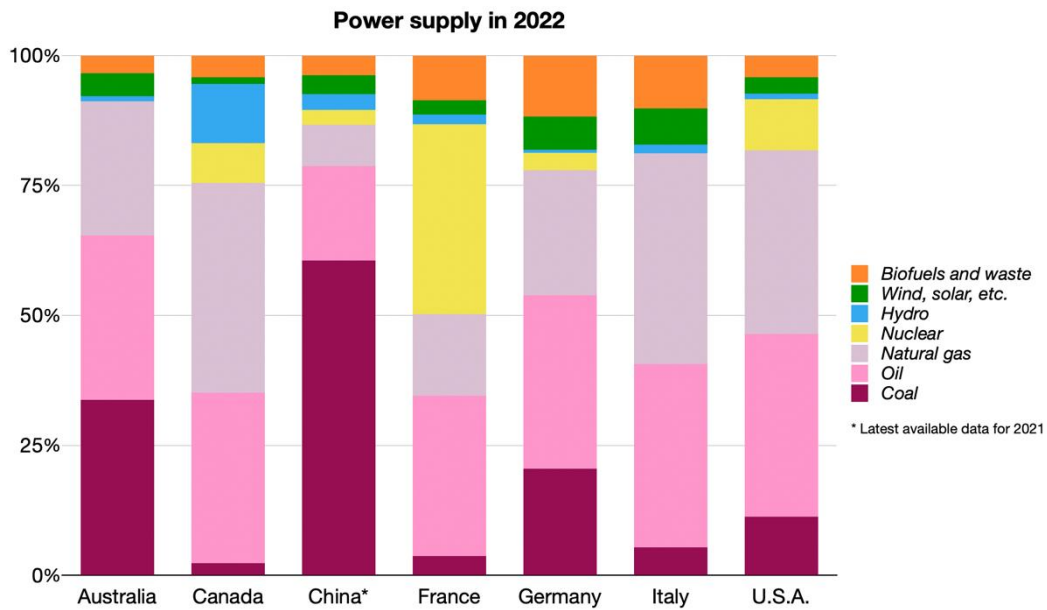


Figure 9 – Power supply breakdown for various countries based on IEA data for 2022, except for China (2021) [102]. For comparative purposes, all values have been expressed in percent.

The electricity being used to power the electrolyser is certainly important. However, the LCA of the wind-powered electrolysis system published in the NREL report [103] shows that the main contributor to GWP and other impact categories is the manufacture of the wind turbines, while the environmental burden associated with the electrolyser operation itself is minimal. Similarly, photovoltaic modules were identified as the main reason for the life-cycle GHG emissions of solar-powered electrolysis (with the electrolytic system purely running on renewables) [72,74].

Since the construction of solar farms, wind turbines, and other renewable energy infrastructure is a transitory activity required once and for all (with maintenance being accounted for separately), its relative incidence per unit mass of hydrogen produced will diminish as the electrolysis yield grows, and the lifetime of the implant increases. For example, according to Palmer et al. [74], the GHG intensity is inversely proportional to the operational lifetime of a solar-powered electrolysis systems. In the meantime, the associated short-term impacts can be mitigated through CCS and acid gas neutralisation technologies [8].

As pointed out by Olindo et al. [30], the life-cycle inventory (LCI) data on specific technologies of electricity production show a wide variability in the literature, which means that, when performing an LCA of electrolytic hydrogen, if grid electricity is to be used either to produce the equipment or to operate the electrolyser, the results will be affected to a large extent by the choice of the inventory data for electricity. Further to this, the electricity mix in Europe, United States, and other regions committed to reaching carbon neutrality is moving towards an increasing share of renewables. As a result, the carbon intensity of electricity is also changing rapidly, and the LCI data in existing databases are often lagging behind, with a gap that is approximately 4-8 years [30].

Different LCIA methods consider different impact categories. As discussed by Valente [104], HyGuide guidelines recommend the use of certain impact categories, including global warming, acidification, eutrophication, photochemical ozone creation potential, primary energy demand (renewable and non-renewable), and additional categories such as land use and ozone depletion [17]. It is therefore surprising that, as already noticed by Bhandari et al. [8], most LCA-based contributions in the literature are dedicated to GHG emissions and GWP, whilst other impact categories, associated for example with rare material depletion, water consumption and land use, are less frequent. Yet, a recent contribution by Terlouw et al. [79] identified the material efficiency of the electrolyser and the land use as the main environmental hotspots in electrolysis powered by renewables. Besides the environmental burden, the extensive land occupation needed for the production of renewable energy and electrolytic hydrogen becomes critical if integrated power generation-electrolysis plants must be installed in confined spaces, such as in urban areas [105] or onboard a ship for the decarbonisation of maritime transportation [22]. The need for critical raw materials and rare metals, such as the iridium and platinum used as catalysts in PEM electrolysers, may also create pressure on the environment [39,41,54,79,106].

Although water is the main feedstock for producing hydrogen via electrolysis, few authors provide accurate data in this regard. Already identified by Simons and Baur in 2011 [107], this gap is still obvious in the literature. Yet, a recent social-life cycle assessment revealed that Saudi Arabia and Oman, in spite of having a huge potential for producing and exporting green hydrogen given the abundance of sun and wind resources, will be disadvantaged in the pursuit of their green hydrogen strategies by the scarcity of freshwater, and by the additional investment cost for water desalination [108]. Similarly, Du et al. [109] argued that scaling up the production of green hydrogen would be especially impactful for those geographic areas that are prone to water stress and chronic risks. Due to the uneven distribution of water resources, the deployment of green hydrogen may finally be jeopardised in specific regions [109].

As a rule of thumb, 9 kg of water are needed to produce 1 kg of H₂, while also producing 8 kg of oxygen as by-product [52]. Based on the data published in 2023 by Pawłowski et al. [45], if all hydrogen was to be produced by electrolysis, this would result in a water requirement of 617 10⁶ m³ per year, which corresponds to 1.3% of the global use of water in the energy sector. This applies to feedstock water. However, water is also used in upstream processes. According to the inventory collected by NREL for a wind-powered electrolysis system analysed from cradle to gate [103], the estimated total consumption of water sums up to 26.7 kg H₂O/kg H₂. Nearly 45% of this water is processed in the electrolyser, while the remaining 55% is needed for manufacturing wind turbines (38%) and hydrogen storage tanks (17%). According to the same NREL report, other inputs to the wind-powered electrolysis system include iron (for the wind turbines and the storage tanks) and limestone (for the turbines' foundations), as well as fossil fuels (coal, oil, and natural gas). A graphical summary is provided by the bar chart in Figure 10, where water was not included owing to the different order of magnitude of its specific consumption.

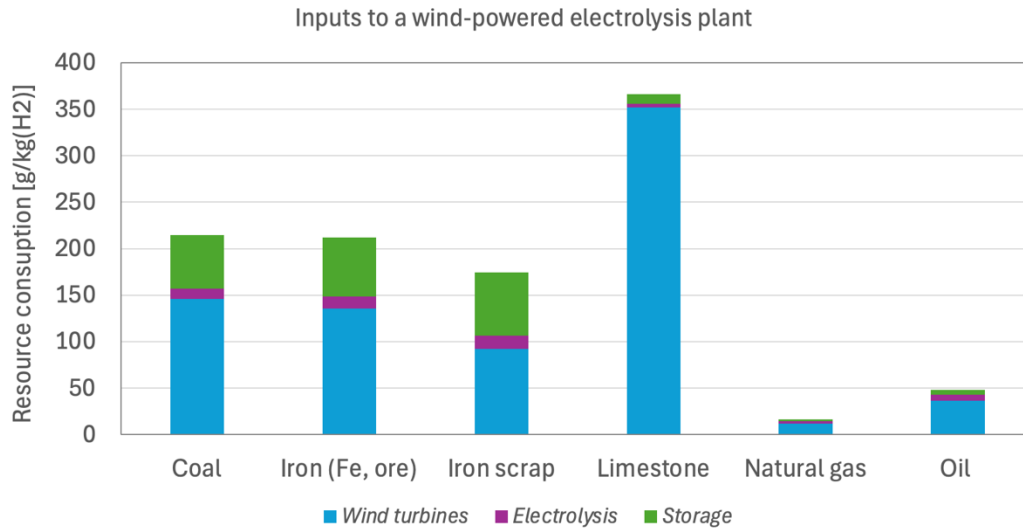


Figure 10 – Main inputs (water excluded) in a wind-powered electrolysis system modelled from cradle to gate according to the data provided in the NREL report [103]. Water could not be included due to the different order of magnitude of its specific consumption.

G. GREEN HYDROGEN DELIVERY

When analysing the literature regarding the LCA of hydrogen, it is worth mentioning that the supply chain can be very complicated and stretch across different countries, because hydrogen is an energy carrier that, by nature, lends itself to long-distance trade [62]. The supply chain may be particularly articulated for green hydrogen, given that, as previously mentioned, geographical areas rich in renewable energy potential, geographical areas rich in electrolyser manufacturing capabilities and geographical areas needing hydrogen imports to satisfy their energy needs not always coincide [62,72,110].

Akin electricity, the delivery of hydrogen to the point of use is made in two steps. In the first step, called transmission, hydrogen is conditioned and stored at a central plant, and then moved from the central plant to a substation. In the second step, namely the distribution, hydrogen is locally made available to end-users that can be private, public, and industrial customers [111]. For long-range delivery, liquefied hydrogen can be transported in tanks or shipped, while compressed gaseous hydrogen can be delivered in tube trailers [112]. Alternatively, hydrogen can travel through dedicated pipelines or even mixed with methane through existing infrastructure [113]. Ammonia and other liquid organic hydrogen carriers (LOHCs) offer alternative pathways for hydrogen transportation over large commercial networks [114]. However, the hydrogen-to-carrier conversion and reconversion pose extra costs and energy requirements, and the LOHC supply chain also implies additional EIs [64,67,115–119].

The LCA of seven different options for the inland delivery of green hydrogen showed that the lowest GWP was caused by compressed hydrogen (gas) moved via pipeline, whereas the worst GWP was attributable to the adoption of an organic carrier with natural gas being used as the heating source for dehydrogenation. Adopting ammonia as the hydrogen carrier similarly produced significant emissions. However, in theory, the GWP could be drastically cut down if ammonia was used in direct ammonia fuel cell vehicles, because this would avoid the energy-intensive and environmentally impactful dehydrogenation process [65].

In terms of cost effectiveness, an analysis published by the European Commission's Joint Research Center (EC-JRC) reached the conclusion that the most convenient hydrogen delivery route must be identified on a case-by-case basis, as it depends on distance, required volume flow rate, final use, and the potential pre-existence of suitable infrastructure [120]. As a general guideline, for distances coherent with the European territory, liquefied hydrogen solutions, and even more so compressed hydrogen pipelines, attain lower costs than chemical carriers do. It is also expected that most natural gas pipelines already existing in Europe can be retrofitted for hydrogen use, and this will plausibly lower the delivery cost for hydrogen (gas). However, chemical carriers become economically preferable over longer distances, due to their lower transport costs. Chemical carriers are thus predicted to enable international import options to the EU from suppliers located, for example, in Chile or Australia [120].

When analysing the electrolytic production and delivery of hydrogen, the precise definition of the system boundaries is critical, because the impacts vary significantly whether a post-production compression or liquefaction step is considered or not. Nonetheless, not all papers are clear in this regard. As for hydrogen compression, the impacts vary depending on the targeted service pressure, which dictates the energy consumption [121]. For example, a noticeable amount of electricity is consumed to compress hydrogen from plant outlet pressure (around 30 bar in pressure alkaline technologies) to tank storage pressure (generally exceeding 200 bar for tube transportation) [33]. Similarly, liquefaction also implies significant EIs [62]. Further to this, additional EIs such as GHG emissions and the formation of fine particulate matter are tied to the use of hydrogen-resistant steel or other specially designed materials for building the storage tanks [71]. The consequences on the environment become more relevant as the storage pressure increases (hydrogen is routinely stored in a pressure range between 350 and 700 bar [122]), because the structural requirements and, thus, the nature and the amount of materials being used for manufacturing the tank are dictated by its internal pressure [123].

H. GREEN HYDROGEN APPLICATIONS

H.1. DECARBONISATION OF HARD-TO-ABATE SECTORS

Hydrogen is often regarded as a viable option for the decarbonisation of hard-to-abate sectors in industry and transportation, which are presently relying on coal, coke, natural gas, diesel, or kerosene as their primary energy resource [29,57,66,78,124–138].

The European Hydrogen Backbone initiative launched in 2021 predicts that the EU+UK will experience a hydrogen demand of around 2'300 TWh (corresponding to 20-25% of the final energy consumption) in order to achieve carbon neutrality by 2050 [139]. In this context, it is estimated that about 1'200 TWh of hydrogen will be needed in industry for steelmaking (180 TWh), ammonia synthesis (113 TWh), fuel production (691 TWh), and process heat generation (217 TWh), and further 300 TWh will be needed in transportation for heavy road freight (217 TWh) and aviation (68 TWh) [78,139]. However, this may cause a burden shift from climate neutrality to other environmental impacts, such as material, water, and land use [39–41].

The ability to realise the European strategy for decarbonisation will hinge on mass production of green hydrogen, which implies the development of adequate infrastructure as a necessary precondition. The capacity of wind and solar power will also need to increase by 50% to meet the green hydrogen volume forecast for EU+UK by 2050 [78]. Various scale-up options were examined by Shen et al. [78] through an LCA-based comparison of 4 different scenarios, including business as usual (baseline condition without any change to the current energy mix in EU+UK), decarbonisation through the adoption of green hydrogen, decarbonisation without green hydrogen through the adoption of blue hydrogen, and decarbonisation without green hydrogen through the adoption of mixed clean energy sources such as biofuel, synfuel, blue hydrogen, and renewable electricity. Interestingly, although the EIs of green and blue hydrogen were comparable in the use phase, they were different over the whole life cycle due to the different production technologies and resource consumption. As for climate change, the advantage of green hydrogen was substantial, with the climate change impact of green hydrogen production being 94% and 82% lower than grey and blue hydrogen, respectively. Green hydrogen also performed better than blue hydrogen in other impact categories including fossil resource depletion (-96%), ozone depletion (-98%), photochemical ozone formation (-72%), and acidification (-60%). However, green hydrogen had worse impacts in land use, water scarcity, mineral resource depletion, particulate matter, eutrophication freshwater, human toxicity, ecotoxicity, and ionizing radiation. Particularly, mineral resource depletion for green hydrogen was higher by nearly 30 times, human toxicity cancer/non-cancer by 5.7/4.1 times, and ecotoxicity by 4.5 times. Ultimately, the total monetized life cycle impacts of blue hydrogen (estimated at EUR 40 billion), largely exceeded that of green hydrogen (EUR 16 billion), mainly due to the costs related to climate change and fossil resource depletion. When the comparison was extended to other decarbonisation routes, for hard-to-abate

sectors in industry the scenario with green hydrogen avoided 91.2% of the climate change impact compared to the business-as-usual condition, 66.3% compared to the scenario with blue hydrogen, and 81.5% compared to the scenario with mixed clean energies. Similar benefits were estimated for the transportation sector, with green hydrogen avoiding 85.9% of the climate change impact compared to business-as-usual conditions, 73.3% compared to the scenario with blue hydrogen, and 45.4% compared to the scenario with mixed clean energies.

H.2. TRANSPORTATION

With a focus on transportation, green hydrogen has been suggested as a crucial means of decarbonisation of road transportation, because the emissions (per km) caused by green hydrogen vehicles are predicted to be much lower than those of conventional fuels [70]. However, it is worth noting that the future evolution of electricity mix is critical in this regard, because the EIs of battery electric vehicles is predicted to drop as the quote of renewable energy in the grid increases, thus offering a competitive alternative to hydrogen vehicles [140].

Hydrogen may be especially appealing for the decarbonisation of heavy-duty vehicles, such as not-electrified trains that are presently powered by diesel engines. However, according to the literature data discussed by Kolahchian Tabrizi et al. [73], the cost of retrofitting a diesel engine to become hydrogen-compatible is similar to the cost of converting to natural gas, and ranges therefore between EUR 8'000 and EUR 12'000. Further to this, hydrogen must be compressed to increase its volume-based energy density, with additional costs (both environmental and financial) associated with the compression operation and the high-pressure storage. If, for financial reasons, retrofitting of the engine is limited to those key changes that are necessary for enabling the fuel conversion without any upgrade, some losses in power are also predicted to occur. As a result, more time may be required to cover the same distance, and performance problems may occur on high-speed trips or freight trains. However, the trip duration would likely stay nearly the same on local routes, where permissible speeds are low, and stops are frequent. Meanwhile, the GWP would drastically drop, with a reduction that could exceed 50% if hydrogen was compressed using solar power. The GWP cut would be less impressive, but still noticeable if the compressor was run on a conventional (fossil fuel-based) electricity grid. Interestingly, if blue hydrogen was used instead of green hydrogen, the GWP would ultimately depend on the entity of potential leaks of methane associated with hydrogen production [73].

Green hydrogen may also be an option for fuelling maritime transportation and river logistics [141]. For example, Mio et al. [41] examined the production of hydrogen to be used as feedstock for 2 trips per day of a medium size ferryboat to navigate full electric for 7 h across the Adriatic Sea and found that the adoption of green hydrogen would result in the lowest environmental impact among all hydrogen types, including grey and blue hydrogen from fossil fuels, and grid hydrogen produced by grid-powered electrolysis. The energy return on energy invested (EROEI, which is an index of the energetic efficiency of the process) would also be very high for electrolytic

hydrogen (14.28 for grid hydrogen and 13.19 for green hydrogen, against 5.48 for grey hydrogen and 4.59 for blue hydrogen), but the levelised cost for green hydrogen would be higher (8.76 for year 2022) than blue hydrogen (5.50).

Tomos et al. [80] adopted a modified LCA approach in order to compare the decarbonisation potential of numerous fuels for international maritime shipping, including green and blue hydrogen, green and blue ammonia, e-methanol (namely, methanol produced from green hydrogen and liquid waste carbon dioxide from industry), bio-methanol, fatty acid methyl ester (FAME) bio-diesel, and bio-methane. Heavy fuel oil was assumed as a benchmark. Instead of scrutinising a particular case study that would be bound to a specific kind of ship and hence difficult to translate to other scenarios, Tomos et al. [80] defined the functional unit of their analysis as the total propulsion energy required by the global fleet over one year (reference year: 2018), which was estimated according to data from the international maritime organisation (IMO). Then, the life-cycle climate change potential of each fuel was determined over a time scale of 100 years (GWP-100). In this calculation, all GHG emissions were factored in, and not just CO₂. Notably, none of the investigated fuels was able to meet the 0-emission target that would be required for the complete decarbonisation of the shipping sector. However, clean burning fuels such as bio-methanol, FAME biodiesel, and green hydrogen scored the strongest GHG emission reductions compared to the heavy fuel oil baseline, as the climate change potential was reduced by 85-94%, 87%, and 74-81%, respectively. Despite the highest decarbonisation potential, the role of methanol becomes uncertain when comparing these results to the number of alternative fuel vessels in operation or on order. Tomos et al. [80] noticed in fact that the number of methanol vessels on order in 2023 was almost three times as much as the existing methanol fleet recorded in the World Fleet Register, but all of them were dual fuel vessels. In dual fuel vessels, the methanol-to-fossil fuel ratio is undetermined. Conversely, although very rare, 100% hydrogen-fuelled vessels were already operational at the time, and the number was predicted to grow under the driving force of hydrogen policies and political commitment [80].

Mio et al. [42] also confirmed that the adoption of photovoltaic green hydrogen (produced by alkaline electrolysis) instead of diesel would sensibly reduce the GWP associated with the activities of a mid-size port like Trieste in Italy. However, it is worth noting that, when the comparison was extended to other potential EIs beyond GWP, diesel-based activities scored lower values (i.e., better environmental performance) in 10 out of the 18 impact categories analysed, mainly due to the smaller amount of electricity needed through the lifecycle. Conceivably, hydrogen from SMR, with and without CCS, performed worse than diesel in numerous categories, and even worst results were attributed to grid hydrogen, namely hydrogen produced with conventional grid-powered electrolysis [42].

H.3. HEATING

Hydrogen has also been proposed as a decarbonisation option for building heating, cooking, and domestic hot water. The household-related heat demand is currently considered an environmental hotspot, being responsible for 36% of the EU's energy-related GHG emissions [142]. Meanwhile, heating and cooking with fossil fuels and biomass account for 53% of fine particulate matter pollution and 8% of nitrogen oxides' emissions in the EU [142]. Besides the environmental concerns, building heating poses geo-political challenges due to the dependence of the EU+UK on fossil fuels [143], which historically had been imported from Russia, and are now being sourced from a variety of suppliers, mainly U.S.A. (petroleum oils and liquified natural gas) and Norway (natural gas in gaseous form) [144].

Famiglietti et al. [69] compared various household heating appliances, including a condensing boiler (CB), a gas heat pump (GHP), and electric heat pump (EHP). Under the ideal hypothesis that the boiler and the gas heat pump will be fuelled by green hydrogen (instead of natural gas) by 2030, the gas heat pump is predicted to entail the best performance in terms of climate change because it uses green hydrogen, whose climate profile is expected to be better than that of the European electricity mix referred to 2030, and because it achieves higher efficiency compared to the boiler. Further to climate change, hydrogen-fuelled devices are forecast to score better than electric heat pumps in most impact categories, but they would become the major contributors to particulate matter formation, various toxicity-related categories, land use, water use, and material resources (mineral/metals). Finally, the electric heat pump would have intermediate impacts between the boiler and the gas heat pump for the photochemical ozone formation and eutrophication terrestrial impact categories.

The contribution by Famiglietti et al. [69] suggests that the advantage of adopting hydrogen for domestic heating, hot water demand, and cooking is still controversial, because a potential burden shift may occur from climate change to other impact categories. This was also confirmed by the study by Shamoushaki and Koh [77] comparing the supply chain of various heat pumps for the decarbonisation of residential constructions in the UK. In order to tackle this conundrum, Weidner and Guillèn-Gosàlbez [82] modified the standard LCA procedure in order to verify the ability of hydrogen-based technologies and other decarbonisation routes to meet the household heating demand while staying within the planetary boundaries. Originally postulated in 2009, planetary boundaries are biophysical thresholds that, if exceeded, are thought to result in catastrophic consequences for humanity [145]. In practice, when conducting the LCA of hydrogen-based heating and other heating scenarios, Weidner and Guillèn-Gosàlbez [82] applied specific characterisation factors taken from the body of literature [146,147] that allowed them to determine the total impacts in 9 different planetary boundary categories. Meanwhile, the planetary boundaries were downscaled to the European context (with a correction factor corresponding to the ratio between European population and global population, around 5.6%) and to the building heating sector (with a correction factor corresponding to the ratio between GHG emissions of the

building heating sector and GHG emissions of the whole economy, around 17.7%). The analysis proved that building heating can stay within planetary boundaries if decarbonisation is pursued through large-scale electrification via heat pumps. Despite being environmentally sustainable, this option is more expensive than the existing system, with abatement costs in the order of 200 EUR per tonne of CO₂. Conversely, it is not possible to stay within the planetary boundaries when using hydrogen solely. The adoption of hydrogen would require a problematic trade-off, because blue hydrogen would be cost-competitive but environmentally unsustainable, whereas green hydrogen would be 2-3 times more expensive than electrification while still surpassing numerous planetary boundaries. In the models developed by Weidner and Guillèn-Gosálbez [82], decarbonisation via hydrogen uptake results to be unfavourable mainly due to the very low efficiency of hydrogen boilers (estimated at 75%) with respect to electrified heat pumps (ranging between 200 and 400%). Another shortcoming of hydrogen is the extremely high cost of delivery to non-grid connected users, even assuming that, besides building new dedicated infrastructure, the natural gas grid already existing in many European countries is suitable for retrofitting to hydrogen.

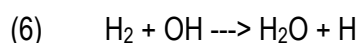
I. OPEN QUESTIONS AND FUTURE DIRECTIONS

Hydrogen, especially if green, is often hailed as the key enabler of climate neutrality. In the EU, it is estimated that hydrogen at scale could close up to nearly 50% of the gap between the emissions forecast in 2050 in the reference technology scenario, where reductions are only achieved through energy efficiency improvement, and the targeted 2-degree scenario, where global warming is kept below 2 °C compared to pre-industrialisation levels [148]. However, as further discussed below, concerns are arising about the effects that a hydrogen economy may have on the environment [21,149].

I.1. HYDROGEN AND CLIMATE CHANGE

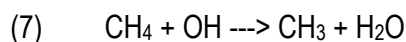
Hydrogen does not absorb infrared radiation, and therefore it is not considered a GHG itself. However, it does have an indirect influence on radiative forcing (which is an indicator of the heating effect caused by GHG in the atmosphere [150]. In other words, H₂ is an indirect GHG [151,152].

Once released to the atmosphere, hydrogen is likely to react with OH groups to form H₂O according to Equation 6:



H is then likely to recombine with O₂ to form HO₂, which is involved in reaction cycles that destroy stratospheric ozone. Conversely, assuming that all other emissions remain the same, an increase in the atmospheric concentration of hydrogen would increase the concentration of tropospheric ozone [151,152].

Meanwhile, the scarcity of OH caused by the reaction in Equation 6 would also prolong the lifetime of CH₄, which is normally regulated by Equation 7:



The lifetime of CH₄ has been calculated to increase by about 1 year for every 1 ppm increase in hydrogen concentration. CH₄ is the second strongest GHG after CO₂, and extending its lifetime would further increase its radiative forcing and, hence, its GWP [151,152].

Changes in the concentration of hydrogen are also predicted to affect atmospheric water vapour. The H₂O budget in the troposphere (which is the lowest region of the atmosphere, stretching from the earth's surface to a height of about 6-10 km) is controlled by hydrological cycles, but increases in atmospheric hydrogen are likely to increase water vapour in the stratosphere (which is the region of the atmosphere above the troposphere, extending to about 50 km above the earth's surface). The radiative impacts of stratospheric water vapour should also be taken into consideration in the context of the indirect climate impact of hydrogen [151,152].

Being a very small molecule, hydrogen in its gaseous form is extremely prone to leak, even more than methane whose molecule is bigger. As a term of comparison, figures published in 2023 by the U.S. Environmental Protection Agency suggest that about 6.5 million metric tonnes of methane leak from the oil and gas supply chain every year, corresponding to around 1% of total production [153]. However, data are very uncertain [154], and on-going surveys indicate that leaked volumes could eventually be much bigger [155,156]. Estimates for hydrogen range from <1% to 20%, but any numbers are largely hypothetical due to the paucity of experimental evidence [51]. The impact of potential leaks along the supply chain becomes even more concerning if hydrogen is produced via SMR, because methane leaks add to hydrogen leaks.

In order to draw attention to emissions, Sun et al. [51] revisited the case studies originally analysed in the “Hydrogen decarbonization pathways” (issued by the Hydrogen Council in 2021 [101]) to account for hydrogen being lost to the atmosphere along the production-to-end use pathway. A list of the hydrogen applications examined by Sun et al. [51] is provided in Table 2. It was demonstrated that, with high methane (2.1%) and hydrogen (10%) emission rates, the GWP of blue hydrogen in the short term (20 years) can be even worse than that of fossil fuel technologies by up to 14% depending on the application. The consequences of methane and hydrogen emissions were predicted to be especially negative in the light-duty vehicle application, because the GWP in the short term was much worse than that of electric vehicles, with values 10-45% higher depending on the specific hydrogen and methane emission levels. Likewise, high hydrogen emissions were proven to be detrimental to the climate benefits of green hydrogen, which were reduced by up to 25% in the short term (20

years), and by up to 13% in the long term (100 years) with respect to the ideal case of negligible hydrogen emissions.

Table 2 – Production-to-end use pathways originally gathered in the “Hydrogen decarbonization pathways” [101], and then revised by Sun et al. [51] to account for hydrogen leaks.

Hydrogen type	Application
<i>Blue hydrogen</i>	Long-distance passenger vehicles
	Ships
	Industrial heat
	Ammonia-based power generation
<i>Green hydrogen</i>	Fertilizer production
	Buses
	Heavy-duty trucks
	Steel making

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While most contributions on climate change only contemplate a time span of 100 years, the results published by Sun et al. [51] suggest that the decarbonisation efficacy of hydrogen actually depends on time. This topic was investigated by Patel et al. [75] in their comparison of various hydrogen production technologies. The GWP was estimated both in the short term and in the long term, with a time horizon of 20 and 100 years, respectively. When considering potential methane leaks (but not hydrogen leaks), the GWP of all methane-derived hydrogen types (grey, blue, and turquoise, as listed in Table 1) turned out to be much higher on the short term than on the long term, with the difference being about 12-25% depending on the specificities of the methane supply chain. The higher GWP at 20 years originated from the fact that methane has a shorter lifetime than CO₂, which means that its GWP over 20 years (estimated at 81-83) is much higher than its GWP over 100 years (estimated at 27-30) [157]. Conversely, Patel et al. [75] calculated that the GWP of green hydrogen remains the same over 20 and 100 years because its production does not rely on natural gas. However, as mentioned above, the

contribution by Patel et al. [75] implicitly assumes that hydrogen leaks are negligible, and hence does not account for the different lifetime of gas species potentially related to the indirect GWP of hydrogen.

Another criticality arising in the LCA of hydrogen technologies is that the GWP on a given time scale, generally 100 years, is routinely calculated as the effect of a one-time pulse of emissions. However, Patel et al. [75] argued that this assumption may be unrealistic, as long as emissions from a running technology occur constantly over time, and this may be responsible for a continuous replenishment of the GHG levels in the atmosphere. As a result, Patel et al. [75] suggested that, in addition to GWP, the climate effect of hydrogen (akin fossil fuels) should be determined as the cumulative radiative forcing from continuous emissions over various time scales. This assessment of climate impacts follows the “technology warming potential” (TWP) approach introduced by Alvarez et al. [158], which was specifically designed for the comparison of different fuel technologies over time. Finally, it should be noted that, especially for research and development purposes, LCAs are often made *ex-ante* (prospective LCAs), which means that potential EIs of emerging technologies are calculated as a function of anticipated future scenarios [159]. As mentioned before, only a minor fraction of (anthropogenic) hydrogen can presently be defined as “green”, i.e., produced via renewable-powered electrolysis. Certainly, green hydrogen volumes are expected to increase in future owing to the wider availability and lower cost of wind- and solar-based energy [81]. The transition to renewables will also mitigate the residual EIs of green hydrogen tied to the manufacture and assembly of the electrolysis system, and to the potential use of back-up power from the electricity grid [62]. This transition will likely be gradual, though. Meanwhile, the decarbonisation of the grid will also reduce the life cycle GHG emissions associated with other types of hydrogen, such as methane pyrolysis (turquoise) hydrogen [39]. Further to this, scaling up the production of green hydrogen to meet the net zero targets by 2050 may come at the expense of other impact categories. For example, a burden shift may be expected from global warming to bio-geochemical flows [81]. The use of critical materials such as platinum-group metals (for example, in PEM electrolyzers [54]) may become both an environmental hotspot and a technological bottleneck, and this warrants the timely identification of substitution possibilities and reprocessing strategies [34]. The multi-faceted complications arising from mass-scale production may ultimately affect the environmental edge of green hydrogen over other hydrogen technologies and alternative decarbonisation pathways, calling for an accurate assessment that takes into consideration multiple impact categories, and not just climate change.

1.2. DECENTRALISED VS. CENTRALISED GREEN HYDROGEN MODELS

Besides the climate-related uncertainties, two major environmental hurdles that may hamper the wider uptake of green hydrogen are the complexities of the distribution pathways and the considerable water consumption [83]. Long-range delivery of hydrogen is accompanied by leaks. Hydrogen storage requires compression or

liquefaction, which are energy-intensive processes, and diesel-fuelled trucks and ships for hydrogen transportation are responsible for GHG emissions. Meanwhile, electrolysis consumes a non-negligible amount of water [160], with the recovery rate after treatment being around 50% [83]. Since water for industrial electrolysis must be pure, American Society for Testing and Materials (ASTM) Type II deionized water is the recommended quality [161]. Achieving this quality requires reverse osmosis followed by an additional polishing treatment, such as ion exchange or electro-deionisation. Interestingly, as pointed out by Winter et al. [83], the need for water treatment opens up new opportunities, because reverse osmosis is quite a versatile technology enabling the consistent production of high-quality water starting from a variety of water feedstocks, including non-conventional sources. As a result, purified seawater, household water, municipal wastewater, and industrial wastewater could all be used as the starting point for electrolysis. Likewise, hydrogen could be produced from the large amounts of wastewater that are generated by carbon capture technologies and extraction processes such as mining. At the same time, water purification takes much less energy than electrolysis, and is also much less expensive. This means that using distributed water sources for hydrogen production in decentralised, small-scale electrolyzers is both technically and economically feasible. Winter et al. [83] estimated that the levelised cost of hydrogen would be minimised for production sites having a capacity in the order of 105 kg per year, corresponding to a distribution distance in the range of 15-40 km. For smaller production capacities, hydrogen would be too expensive due to the high equipment costs relative to the plant's yield rate. For larger scales, electrolysis plants would be more distant from one another (assuming that the hydrogen use rate per unit area is constant), and this would increase the transportation distance and hence the hydrogen price and CO₂ emissions. Small-scale distributed electrolyzers would be even more convenient with respect to large-scale centralised plants if high CO₂ taxes ("carbon taxes") were applied, because the longer transportation distance would result in higher emissions and hence in additional penalties [83].

Even though distributed green hydrogen production would cut down the transportation-related costs and emissions while also enabling water mining from unconventional sources, many researchers and policymakers agree that electrolyser capacity needs to be scaled up by orders of magnitude in order to meet the climate neutrality target by 2050 [74,162]. Accordingly, Krishnan et al. [55] predicted that future electrolyzers will have larger stacks with higher current density to increase the hydrogen production rate and boost the electrolyser capacity from the megawatt (MW) scale to the gigawatt (GW) scale. In 2020, the International Renewable Energy Agency (IRENA) explored potential ways of reducing the cost of green hydrogen and reached the conclusion that increasing the module size and improving the design of the electrolyser may have substantial advantages on cost, to the point that scaling up the plant size from 1 MW (typical in 2020) to 20 MW would be enough to reduce costs by over a third [163]. However, deploying green hydrogen economies at scale may be halted by the difficult procurement of materials, and substitutes will be needed to replace rare and expensive critical materials [164]. Scaling up the size of electrolyzers also means scaling up the volume of materials that must be

managed at the end of life of the plant. Metals belonging to the platinum group and other rare elements are still challenging to recover due to the low TRL of the recycling technologies and due to the uncertainty about the volumes of material that can be treated [55,165].

Finally, it is worth mentioning that there are no large-scale green hydrogen plants in operation, which makes it very difficult to obtain verified primary data for LCA studies [74]. As a result, the assessment of potential EIs must be based on expected scenarios, technology development curves, and directives issued at local and global levels [81]. As accurate as they can be, these assumptions are still subject to uncertainty [116].

I.3. RESEARCH OPPORTUNITIES

Research is now being geared towards the development of new water-splitting routes [166–169]. In photoelectrochemical (PEC) electrolysis, for instance, the (photo)electrodes, which are made of special semiconductor materials and electrocatalysts, can absorb photons from sunlight and use the energy to split water molecules into hydrogen and oxygen. Even though PEC electrolysis offers the exciting opportunity of producing hydrogen from solar radiation directly (“photo-hydrogen” or “super-green hydrogen”), the technology readiness level (TRL) is still low (below 4), and the process for the moment requires an electrical bias to overcome overpotentials and support solar energy conversion. Additional research is needed to scale up PEC hydrogen, especially to prolong the average lifetime of the photoelectrodes, which is currently found in the order of hours, and to lower the energy for fabricating the photoelectrodes, which now exceeds 300 MJ/m² (energy per unit area of the photoelectrode). For unassisted PEC, the solar-to-hydrogen (STH) efficiency is also low, being currently in the order of 10%. According to the ex-ante LCA published by Rumayor et al. [76], standing the STH at 10%, the average lifetime of the photoelectrodes should be increased to at least 7 years for PEC to compete with conventional electrolysis in terms of GWP, even assuming that efficient processes are used to fabricate the PEC cells (<500 MJ/m²). The situation is yet more challenging when resource depletion is considered (fossil abiotic depletion potential, f-ADP). Compared with the impacts of wind-powered PEM electrolysis, the STH should be increased to around 15% for PEC to be a viable option. If an electrical bias is applied, the energy consumption intake of the PEC system increases, and the technological requirements that would make PEC electrolysis more sustainable than conventional electrolysis increase accordingly, such that STH should reach 15% and durability should be 10 years [76].

Finally, in order to meet the United Nations’ Sustainable Development Goals (SDGs), social concerns should be taken into consideration in addition to environmental and economic ones. Although social-life cycle assessment (S-LCA) is still an emerging area of research, an increasing number of contributions are bringing to light social hotspots potentially associated with green hydrogen [170]. If compared to grey hydrogen, green hydrogen has shown to perform poorly in various social indicators due to the complexity of its supply chain, wherein key

components of the electrolyser and the renewable energy infrastructure must be sourced from various parts of the world [108]. While the deployment of a green hydrogen economy at scale is expected to improve the performance of green hydrogen in terms of both economic competitiveness and environmental sustainability, socio-geopolitical factors still need additional attention.

J. CONCLUSIONS

In addition to rich information from the archival literature and numerous reports and websites, 35 research papers were analysed to determine how a green hydrogen economy is predicted to affect the environment based on life cycle assessment (LCA). In the absence of a standardised nomenclature, in this literature survey green hydrogen has been defined as hydrogen produced via water electrolysis powered by renewables, and the state of the art has been narrowed down to papers published from 2019 onwards in order to provide an up-to-date description of the field. The analysed contributions cover different phases of the green hydrogen supply chain, including production, delivery and use. Within each phase, there appears to be a strong methodological variability across the reviewed papers, which differ by goal, system boundaries, and life cycle impact assessment (LCIA) methods. Although most contributions refer to the European context, the European Union guidelines for the LCA of hydrogen production are largely missing from the reviewed literature. Consequently, a direct comparison of the results is unfeasible. However, it is possible to draw the following conclusions:

- The contribution of green hydrogen to climate change largely depends on the electricity used to power the electrolyser. In order to be acknowledged as a “zero emission” energy vector, green hydrogen must be produced via electrolysis powered by renewables. If electricity from the grid is necessary to supplement natural energy sources (which are typically discontinuous over time), the global warming potential (GWP) of green hydrogen is affected by the grid mix, which is different for different countries and which is expected to change in the future owing to decarbonisation initiatives.
- Further to this, electricity is needed to build the electrolyser, the renewable power generation plant, and other equipment (balance of plant, electronics, etc.). In a life-cycle perspective, the environmental impacts associated with this electricity will carry over to green hydrogen.
- Considerable environmental hotspots can be identified in water consumption, which may be critical and jeopardise the deployment of green hydrogen in those geographical areas that are poor in water resources, and land use, which takes into account not only the electrolyser, but also the solar or wind farm or other renewable power generation plant needed to run the electrolyser.
- Rare metals and critical materials are employed in the electrolyser (especially for polymer electrolyte membrane (PEM) electrolysis) and in the renewable power generation plant (especially in photovoltaic

cells). Presently, there is not a clear pathway towards the recovery of these materials. Broadly speaking, there is a gap in the literature regarding the “end of life” stage of green hydrogen, particularly regarding the disposal of the electrolyser.

- The supply chain of green hydrogen may be very articulated and stretch across countries and continents, because areas rich in renewables, exporters of electrolysis technology, and final users of hydrogen rarely coincide. Long-haul delivery of hydrogen is responsible for environmental impacts, because gaseous hydrogen is prone to leak, and liquid hydrogen or liquid organic hydrogen carriers must be transported. Although not a GHG itself, hydrogen may cause indirect climate change. Meanwhile, the logistics for transportation also affect the environment.
- Points of interest for future research include the development of more efficient technologies for the conversion of solar energy to hydrogen, and the analysis of the social implications of a green hydrogen economy at scale.

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APPENDIX: SUPPLEMENTARY INFORMATION

Table SI.1 – Relevant reviews and reports providing a survey of LCA applied to hydrogen production. Note: Reference numbers correspond to those in the main text.

Reference	Journal/Source	Year	Scope of the review
[8] Bhandari et al., Life cycle assessment of hydrogen production via electrolysis – a review	Journal of Cleaner Production	2014	LCA of hydrogen production technologies, most of which employing electrolytic technologies
[20] Chelvam et al., A review on the environmental performance of various hydrogen production technologies: An approach towards hydrogen economy	Energy Reports	2024	Survey of LCA applied to various hydrogen production technologies and proposal of a way forward for LCA application on hydrogen in developing countries
[21] Eh et al., Circular hydrogen economy and its challenges	Chemical Engineering Transactions	2022	LCA the identification of feasible and sustainable hydrogen production pathway(s) in the broader context of a circular hydrogen economy
[22] Elrhoul et al., Review of green hydrogen technologies application in maritime transport	International Journal of Green Energy	2023	Possible onboard methods for green hydrogen production, its storage and consumption by various marine propulsion systems
[23] Gonzales-Calienes et al., Life cycle assessment of hydrogen production pathways in Canada	Report of National Research Council Canada	2022	Development of an LCA-based approach to assessing the carbon intensity of hydrogen, including definition of system boundaries and building life cycle inventories for a Canadian context
[24] Hamed et al., A review on blue and green hydrogen production process and their life cycle assessments	IOP Conference Series: Earth and Environmental Science	2023	Implications of the production of both green and blue hydrogen as determined by LCA
[25] Hassan et al., Recent review and evaluation of green hydrogen production via water electrolysis for a sustainable and clean energy society	International Journal of Hydrogen Energy	2024	Water electrolysis and photo-electrolysis for green hydrogen production and their environmental aspects
[26] Iyer et al., Electrolyzers for hydrogen production: Solid oxide, alkaline, and proton exchange membrane	Report of Argonne National Lab. (ANL), USA	2022	Overview of major water electrolysis technologies, with a detailed bill of materials for these technologies that has been incorporated in the updated Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) 2022 model
[32] Kanz et al., Review and harmonization of the life-cycle global warming impact of PV-powered hydrogen production by electrolysis	Frontiers in Electronics	2021	Harmonisation and comparison of LCA results for the GWP of solar-powered green hydrogen
[27] Maniscalco et al., Critical review of life cycle assessment of hydrogen production pathways	Environments	2024	LCA of different hydrogen production methods for their emissions/global warming potential
[28] Melideo et al., Life cycle assessment of hydrogen and fuel cell technologies	Report of the European Commission's Joint Research Center (EC-JRC)	2020	Inventory of LCAs for various hydrogen technologies and processes based on 73 Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) founded projects

[29] Mohammad et al., Assessing the sustainability of liquid hydrogen for future hypersonic aerospace flight	Aerospace	2022	Applications of liquid hydrogen in aerospace projects and comparison of LCA emissions of grey, blue, and green hydrogen for 2030 vs. conventional fuel (JP-7 and JP-8)
[30] Olindo et al., Life cycle assessments on battery electric vehicles and electrolytic hydrogen: The need for calculation rules and better databases on electricity	Sustainability	2021	Methodological contribution regarding the consequences that choices on electricity data may have on the LCA results for hydrogen
[31] Wilkinson et al., Review and meta-analysis of recent life cycle assessments of hydrogen production	Cleaner Environmental Systems	2023	Meta-analysis of 99 LCAs of hydrogen production published between 2015 and 2022, categorised based on geography, production method, energy source, goal and scope

Table SI.2 – Details about the LCA of green hydrogen and its supply chain in the selected research papers. Note: Reference numbers (Ref.) correspond to those in the main text.

Ref.	Paper (First Author, Title)	Journal	Year	Geograph y	System boundary	Functional unit	Software	Background database	LCIA method	Impact categories/ damages	Main results	Emissions/GWP/Climate change	Notes on LCA	Kind of electrolysis	Power used	Compression and/or liquefaction	Delivery	Application
[64]	Akhtar, Comparative sustainability assessment of a hydrogen supply network for hydrogen refueling stations in Korea	Green Chemistry	2021	Republic of Korea	Cradle-to-gate	1 kg of hydrogen	SimaPro v. 9.1.1.1	Ecoinvent v. 3.6	CML-IA baseline v. 3.06 midpoint	9 impact categories	High environmental impact for green ammonia, but predicted improvement by 2030	GWP of green hydrogen supply routes from hydrogen production to hydrogen refueling station in the Republic of Korea 6.81 kg CO ₂ eq/kg H ₂ for hydrogen production via catalytic cracking of imported green ammonia 5.35 kg CO ₂ eq/kg H ₂ for domestic green hydrogen production at a centralized location in Korea 4.57 kg CO ₂ eq/kg H ₂ for on-site hydrogen production via water electrolysis at hydrogen refuelling station powered by solar electricity from the city grid	- LCA based on process simulations - Sensitivity analysis	Alkaline, 33 bar	Solar City grid, fully renewable	Compression if required, depending on the delivery pathway	From Australia to Republic of Korea as liquid NH ₃ or From central electrolysis plant to refuelling station, 100 km away	Transportation: Hydrogen supply network for refuelling stations in Korea
[65]	Akhtar, Life cycle assessment of inland green hydrogen supply chain networks with current challenges and future prospects	ACS Sustainable Chemistry & Engineering	2021	Western Australia	Cradle-to-gate	1 kg of hydrogen at 15 °C, 700 bar, and 99.99 wt % purity for fuel cell vehicle at the refuelling station	SimaPro v. 9.1.1.1	Ecoinvent v. 3.6, allocation at the point of substitution	CML-IA baseline v. 3.06	11 impact categories	- Hydrogen delivery as compressed gas via pipeline has the lowest GWP (1.57 kg CO ₂ eq./kg H ₂) - Delivery via liquid organic carrier has the highest emissions (3.58 kg CO ₂ eq./kg H ₂)	GWP of different green hydrogen delivery pathways ranging from: 1.57 kg CO ₂ eq/kg H ₂ for delivery by compressed gas via pipeline to: 3.58 kg CO ₂ eq/kg H ₂ for delivery by liquid organic hydrogen carrier with natural gas as a heating source		Alkaline	Wind	Compression to different pressures if required, depending on the delivery pathway, or liquefaction, or conversion to liquid organic carrier	Seven inland delivery scenarios (100 km, or 400 km) to a generic hydrogen refuelling station	General application: Decarbonisation of transportation
[66]	Bacatelo, Life cycle assessment of synthetic natural gas production from captured cement's CO ₂ and green H ₂	Journal of CO ₂ Utilization	2024	Portugal	Cradle-to-gate	1 metric tonne of cement	SimaPro v. 9.5	Ecoinvent v. 3.9.1, attributional Primary data from Portuguese survey (data to 2018)	EN15804 +A2 (adaptation of Environmental Footprint (EF) 3 method, customized for Environmental Product Declaration (EPD) of construction products)	12 impact categories	- If compared to ordinary Portland cement, circular Portland cement performs better in climate change and fossil resource use - Trade-offs are evident in acidification, water use, and minerals and metals resource consumption - The electrolysis system is a critical contributor due to the high electricity demand, and its environmental impact depends on the renewable electricity source	Climate change, total, associated with cement production: 7.54E+02 kg CO ₂ eq/1 m ³ cement for conventional ordinary Portland cement production 6.26E+02 kg CO ₂ eq/1 m ³ cement for circular Portland cement using hydrogen from solar energy 4.33E+02 kg CO ₂ eq/1 m ³ cement for circular Portland cement using hydrogen from solar/wind mix energy 2.41E+02 kg CO ₂ eq/1 m ³ cement for circular Portland cement using hydrogen from wind energy	- LCA of circular cement through post-combustion calcium looping, including production of synthetic natural gas and electricity as by-products, where green hydrogen is merely a reactant to produce synthetic natural gas - Disparity in TRL among the individual plants involved - Data supplemented with process simulations - Sensitivity analysis	Alkaline	Wind Solar Wind and solar mix	NO	NO	Construction: Circular Portland Cement, whereby green hydrogen is used for producing synthetic natural gas (SNG)
[67]	Balaji, Sailing towards sustainability: Offshore wind's green hydrogen potential for decarbonization in coastal USA	Energy & Environmental Science	2024	United States (USA)	Cradle-to-gate	1 kg of hydrogen delivered to the shore	OpenLCA v. 1.11.0	Ecoinvent v. 3.9.1	ReCiPe 2016 v1.03, midpoint (H) method	GWP 100	GHG emissions ranging from 0.6 kg CO ₂ eq./kg H ₂ to 3.00 kg CO ₂ eq./kg H ₂ , better than grey hydrogen and below the US Department of Energy benchmark for the well-to-gate GHG emissions (4 kg CO ₂ eq./kg H ₂)	GHG emissions of "wind" hydrogen produced offshore and delivered to coastal states of the U.S.A. ranging from 0.60 kg CO ₂ eq/ kg H ₂ to 1.50 kg CO ₂ eq/kg H ₂ in the compressed gaseous hydrogen pipelines pathway and from 0.97 kg CO ₂ eq/kg H ₂ to 3.15 kg CO ₂ eq/kg H ₂ in the liquefied hydrogen shipping pathway depending on the distance/state	- Feasibility study based on wind potential of different American states - Cost analysis	Not specified, with water desalination	Wind, offshore	Compression to 700 bar OR Liquefaction	Delivery from offshore wind farm to coastal area, at state level and at regional-hub level	General application: Decarbonisation
[40]	Barbera, Sustainability analysis of hydrogen production processes: A comparison based on sustainability indicators	Chemical Engineering Transactions	2022	Not specified	Not specified	Not specified	Not specified	Ecoinvent	Environmental Footprint (EF)	16 impact categories plus Energy return on energy invested (EROEI) Levelized Cost of Hydrogen (LCOH)	- The best technology in terms of energy and cost impact is "solar" green hydrogen - Green hydrogen shows the highest values for carcinogenic or non-carcinogenic effects on human health, and for resource depletion in water, minerals and metals, and used land	-- (normalised values)	- LCA based on Process Simulations - Energy and financial indicators	Alkaline	Solar	NO	NO	General application: Decarbonisation
[34]	Bareiß, Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems	Applied Energy	2019	Germany	Cradle-to-gate	1 kg of dried hydrogen produced in Germany in a PEM plant, with a standard quality of 5.0 and 30 bar pressure at 60 °C operating temperature	SimaPro	Ecoinvent v. 3.3, attributional	ReCiPe midpoint	6 impact categories	- With 2017 electricity mix of Germany, the GWP corresponds to 29.5 kg CO ₂ eq./kg H ₂ ; - With the electricity mix modelled for 2050, emissions can be reduced to 11.5 kg CO ₂ eq./kg H ₂ - Using only the 3000 h of excess power from renewables in a year will allow for the reduction to 3.3 kg CO ₂ eq./kg H ₂	GWP of green hydrogen production by proton exchange membrane (PEM) electrolysis: 29.5 kg CO ₂ eq/kg H ₂ for today's electricity mix 11.5 kg CO ₂ eq/kg H ₂ for 2050 base-load operation scenario 3.3 kg CO ₂ eq/kg H ₂ for PEMWE operating 3000 h using only electricity produced by renewable sources	- Future scenarios accounted for, from 2017 to 2050	PEM, 30 bar	Wind, onshore (constrained), and solar mix Other scenarios (grid in 2017 and grid in 2050)	NO (but purification and drying considered)	NO	General application: Decarbonisation, with hydrogen production volumes optimised for fuel cell vehicle transportation
[68]	Chidire, Life cycle assessment of green hydrogen production via geothermal energy-driven electrolysis	IEEE conference paper	2023	Not specified	Cradle-to-gate	1 kg of hydrogen produced	SimaPro	Ecoinvent v. 3.5	Not specified	GWP	Low GWP of 3.67 kg CO ₂ eq./kg H ₂	GWP of green hydrogen production with geothermal energy: 3.67 kg CO ₂ eq/kg H ₂	Geothermal power through Organic Rankine Cycle	PEM	Geothermal	NO	NO	General application: Decarbonisation

[57]	Chirone, Carbon capture and utilization via calcium looping, sorption enhanced methanation and green hydrogen	Fuel	2022	Italy (but power plant model in Spain)	Cradle-to-gate	1 kg of methane	Not specified	Ecoinvent v. 3.5, cut-off method	Environmental Footprint (EF) 2.0 Normalized to the reference impact per person of EU-28	12 impact categories	- Production cost of methane higher than that of natural gas (0.66 vs 0.17 EUR/Nm ³), but lower than that of biomethane (1 EUR/Nm ³) - Environmental performance better in some categories and worse in others	-- (normalised values)	- Techno-economic analysis - LCA of methanation, rather than green hydrogen	PEM	Not specified	NO	NO	Chemical industry: PEM integrated in a multi-unit reactor for methanation of flue gases
[46]	Das, Multi-criteria decision-making for techno-economic and environmentally sustainable decentralized hybrid power and green hydrogen cogeneration system	Renewable and Sustainable Energy Reviews	2024	India, Punjab, Churpur	Cradle-to-gate	Electricity of 1 kWh and 1 kg hydrogen	SimaPro v. 9	Ecoinvent v. 3.1	ReCiPe 2016 v. 1.1, midpoint Eco-indicator 99®, endpoint	18 impact categories (midpoints) 3 damage categories (endpoints)	The solar-wind-diesel-battery-electrolyser combination is the best option for techno-economic and environmental sustainability through multi-criteria decision-making	CO ₂ emissions caused by a decentralised hybrid cogeneration unit that produces power and 'green' hydrogen: 1564 kg CO ₂ /year for solar energy/wind energy/Li battery/diesel generator combination 1991 kg CO ₂ /year for solar energy/Li battery/diesel generator combination 2861 kg CO ₂ /year for wind energy/Li battery/diesel generator 85198 kg CO ₂ /year for diesel generator/Li battery combination (baseline)	Techno-economic optimisation	Not specified	Various combinations of wind, solar, diesel generator, possibly with battery	NO	NO	General application: Decarbonisation in remote areas
[52]	de Kleijne, The many greenhouse gas footprints of green hydrogen	Sustainable Energy & Fuels	2022	Europe	Not specified (cradle to gate)	1 kg of hydrogen produced	Not specified	Ecoinvent v. 3.7.1	ReCiPe 2016 (H) v1.05, midpoint	GWP (GHG) footprint	Wind-powered green hydrogen scoring the best; solar-powered green hydrogen second best, similar to blue hydrogen	GHG footprint of hydrogen production by different methods: 0.4–0.8 kg CO ₂ eq/kg H ₂ for green hydrogen powered by offshore wind (depending on oxygen co-production) 1.7–4.4 kg CO ₂ eq/kg H ₂ for green hydrogen production using solar energy 6.3–16.6 kg CO ₂ eq/kg H ₂ for electrolytic hydrogen production using the 2020 EU grid mix 2.1–5.6 kg CO ₂ eq/kg H ₂ for electrolytic hydrogen production using a cleaner 2030 EU grid mix	Multifunctionality approach: Potential valorisation of co-produced oxygen	PEM	Wind (offshore) Solar	Compression to unspecified pressure	NO	General application: Decarbonisation
[69]	Famiglietti, Heat pumps for space heating and domestic hot water production in residential buildings, an environmental comparison in a present and future scenario	Energy Conversion and Management	2023	European Union + United Kingdom	Cradle-to-grave	1 kWh of thermal energy provided for space heating and domestic hot water service	Brightway2	Ecoinvent v. 3.8, consequ., system expansion substitution method Cut-off rule set at 1%	Environmental Footprint (EF) 3.0	16 impact categories	- Despite the increased renewable share, the use phase of the heating devices remains the most significant for both temporal scenarios, contributing to 91% of the environmental profile - Except for the higher footprint in 2020 compared to the electric heat pump, the gas absorption heat pump offered a lower environmental profile than the others in all the scenarios analysed	Climate change associated with thermal energy provided for space heating and domestic hot water service 0.276-0.277 kg CO ₂ eq/kWh _{th} for condensing boiler (depending on the building's status: old, renovated or new) 0.198-0.200 kg CO ₂ eq/kWh _{th} for gas absorption heat pump 0.170-0.196 kg CO ₂ eq/kWh _{th} for electric heat pump	- LCA of heating devices, rather than green hydrogen - Different time points at 2020 and 2030 - Results evaluated by error propagation using Monte Carlo (MC) simulation method	Alkaline, pressurised	Wind, solar, and hydro mix	Compression to 70 MPa	Delivery to point of use 100 km away, compressed and transported in a diesel-powered truck (16-32 t of gross capacity and average load factor of 5.79 t)	Heating devices: Condensing boiler (CB) and (air-source) gas(-driven absorption) heat pump (GHP)
[70]	Gerloff, Comparative life-cycle-assessment analysis of three major water electrolysis technologies while applying various energy scenarios	Journal of Energy Storage	2021	Germany	Cradle-to-grave	1 kg of hydrogen	Umberto+	Ecoinvent v. 3.5, cut-off method	ILCD 2.0 midpoint 2018 except for IPCC 2013 used for GWP Impact indicators with level I or level II of recommendation	8 impact categories	Emissions decrease with an increasing share of wind and solar energy in the energy mix	GWP of electrolytic hydrogen when used as a fuel for cars and for electricity generation (assuming that 1 kg of H ₂ corresponds to a range of 100 km), including EoL of electrolyser from 0.2687 kg CO ₂ eq/km (2019 electricty mix) down to 0.0290 kg CO ₂ eq/km (renewable energy) for alkalyne electrolysis from 0.2794 kg CO ₂ eq/km (2019 electricty mix) down to 0.0294 kg CO ₂ eq/km (renewable energy) for PEM electrolysis from 0.2348 kg CO ₂ eq/km (2019 electricty mix) down to 0.0384 kg CO ₂ eq/km (renewable energy) for solid oxide electrolysis	Assumptions were made regarding the total manufacturing energy of components, which is hardly covered by ecoinvent	Alkaline PEM Solid oxide	Wind and solar mix	Compression, pressure not specified	NO	General application: Energy generation and alternative fuel in cars
[48]	Gerloff, Environmental costs of green hydrogen production as energy storage for renewable energies	MRS Energy & Sustainability	2023	Germany	Not specified (cradle to gate)	1 kg of hydrogen	Umberto LCA+ v. 3.5	Ecoinvent CE Delft for environmental prices	ILCD 2018 midpoint, except IPCC 2013 for GWP	8 impact categories	The environmental cost of steam methane reforming (SMR) exceeds that of green hydrogen even if climate change is the only impact category considered for SMR (against 8 impact categories for green hydrogen, climate change included)	Climate change associated with green hydrogen production using solar energy: 5.27 (alkalyne), 5.42 (PEM), 5.78 (solide oxide) kg CO ₂ eq/kg H ₂ using wind energy: 1.74 (alkalyne), 1.74 (PEM), 2.89 (solide oxide) kg CO ₂ eq/kg H ₂ using hydro energy: 2.86 (alkalyne), 2.90 (PEM), 3.81 (solide oxide) kg CO ₂ eq/kg H ₂	- LCA based on previous contribution (Gerloff, 2021) - LCA applied to estimating environmental costs (aka damage costs, obtained as the environmental impacts of green hydrogen production multiplied by environmental prices) - CO ₂ emissions (climate change) is the only impact category considered for steam methane reforming due to lack of data	Alkaline PEM Solid oxide	Wind (onshore) Solar Hydro (non-alpine reservoir)	Not specified	Not specified	General application: Decarbonisation
[71]	Güven, Offshore wind-driven green hydrogen: Bridging environmental sustainability and economic viability	International Journal of Hydrogen Energy	2024	Turkey, Aegean Sea (Bozcaada)	Not specified (cradle to gate)	Not specified (1 kg of hydrogen)	GREET 2023	GREET 2023	ReCiPe 2016	GWP 20 GWP 100 Fine Particulate Matter Formation	Despite the good environmental performance and regardless of various incentives and tax scenarios explored, Internal Rates of Return (IRR) of offshore wind-driven hydrogen fall below the anticipated cost of equity, indicating non-profitability	GWP of offshore wind-driven green hydrogen generation system: GWP-20: 0.700 kg CO ₂ eq/kg H ₂ GWP-100: 0.753 kg CO ₂ eq/kg H ₂	- Combined LCA and and life cycle cost analysis (LCC) - Global Climate Models (GCMs) applied to forecast wind speeds - Sensitivity analysis for cost analysis	PEM	Wind, offshore	Compression to 500 bar	NO	General application: Decarbonisation

[39]	Hermesmann, Green, turquoise, blue, or grey?	Progress in Energy and Combustion Science	2022	Germany	Cradle-to-gate	1 kg of hydrogen at 30 bar that becomes available at the production site	Not specified	Ecoinvent v. 3.6, cut-off method By-products by avoided burden method	Environmental Footprint (EF) 2.0	16 impact categories (main discussion for GWP)	- GWI largely depends on the electricity used for electrolysis; - Potential burden-shifting for water, land, and rare materials use	Global warming impact of electrolytic hydrogen production by PEM: 34.85 kg CO ₂ eq/kg H ₂ with "present-day" electricity mix in Germany, without by-products; 31.96 kg CO ₂ eq/kg H ₂ with "present-day" electricity mix in Germany, with by-products; 28.50 kg CO ₂ eq/kg H ₂ with "future" electricity mix in Germany, without by-products; 25.61 kg CO ₂ eq/kg H ₂ with "future" electricity mix in Germany, with by-products; Plus various terms of comparison (blue/turquoise hydrogen)	- Oxygen computed as by-product - Sensitivity analysis - Future scenarios accounted for, from 2017 to 2050	PEM, 30 bar	Wind, onshore/offshore , and solar mix	NO	NO	General application: Decarbonisation
[72]	Khan, Strategies for life cycle impact reduction of green hydrogen production	International Journal of Hydrogen Energy	2024	Australia	Cradle-to-grave	Generation of 1000 tonnes of hydrogen produced over the lifetime of electrolyser system driven by dedicated solar/wind farms	OpenLCA	Ecoinvent v. 3.4	ReCiPe 2016 (H)	7 impact categories (normalised against the "lifetime amount of hydrogen")	While the energy source has the most impact, material and manufacturing inputs associated with electrolyser production are increasingly significant as the scale of hydrogen output expands	GWP of green hydrogen production by stages: manufacturing of electrolyser: 0.1-0.2 kg CO ₂ eq/kg H ₂ (depending on energy) for alkalyne and PEM electrolysers; transportation of electrolyser from Germany to Australia: ~0.0220 kg CO ₂ eq/kg H ₂ for alkalyne electrolyser; ~0.0203 kg CO ₂ eq/kg H ₂ for PEM electrolyser; operating: 0.7-3.1 kg CO ₂ eq/kg H ₂ for alkalyne electrolyser; 0.6-3.0 kg CO ₂ eq/kg H ₂ for PEM electrolyser; Note: For manufacturing stage: GWP reduced through end-of-life strategies by 70% for alkalyne electrolyser, and by 26.52% for PEM electrolyser	- LCA of an electrolyser, rather than green hydrogen - Ex-ante analysis - Uncertainty analysis	Alkaline PEM	Wind Solar	NO	NO	General application: Decarbonisation (LCA of the electrolyser)
[73]	Kolahchian Tabrizi, Retrofit of diesel engines with H ₂ for potential decarbonization of non-electrified railways: Assessment with lifecycle analysis and advanced numerical modeling	Energies	2024	Italy	Well-to-wheel	Not specified	Not specified	Ecoinvent v. 3.5, cut-off method	Not specified	GWP	Carbon footprint of train reduced from 4.27 to less than 2 kg CO ₂ eq./km (- 56%) by changing blue hydrogen to green hydrogen	Carbon footprint of train transportation: 1.87 kg CO ₂ eq/km for green hydrogen produced and compressed via solar energy 2.79 kg CO ₂ eq/km for green hydrogen produced via solar energy, but compressed using Italian grid electricity 3.80 kg CO ₂ eq/km for blue hydrogen 4.27 kg CO ₂ eq/km for diesel used as the fuel	- The fuel consumption of both trains (diesel or hydrogen-fuelled) is estimated with numerical one-dimensional simulations - After retrofitting the train, the engine traction power is reduced from 600 to 400 kW due to limit costs - Sensitivity analysis of the methane leakage rate	Not specified	Solar	Compression to 800 bar	NO	Transportation: Hydrogen-fuelled engine of non-electrified train
[55]	Krishnan, Prospective LCA of alkaline and PEM electrolyser systems	International Journal of Hydrogen Energy	2024	The Netherland	Cradle-to-gate	1 kg of hydrogen produced	SimaPro	Ecoinvent	Environment Footprint (EF) 3.0 midpoint (as per PEF)	10 impact categories as per FC-HyGuide plus Human toxicity: Cancer and non-cancer Resource use, Minerals & Metals	No clear winner emerges between alkaline and PEM electrolysers in relation to environmental impacts	GWP of hydrogen production, present and near future: 2.08 kg CO ₂ eq/kg H ₂ for alkalyne electrolysis, present 1.15 kg CO ₂ eq/kg H ₂ for alkalyne electrolysis, advanced 1.79 kg CO ₂ eq/kg H ₂ for PEM electrolysis, present 1.03 kg CO ₂ eq/kg H ₂ for alkalyne electrolysis, advanced	- Prospective LCA accounting for future development in electrolyser design - NO end-of-life or recycling of materials due to the low TRL and the uncertainty regarding the amount of material that can be recycled - Sensitivity analysis of current density and catalyst loading	Alkaline PEM	Wind, offshore, supplemented with grid electricity	NO	NO	General application: Decarbonisation (LCA of the electrolyser)
[4]	Lal, Climate sustainability through a dynamic duo: Green hydrogen and crypto driving energy transition and decarbonization	PNAS	2024	United States (USA)	Not specified	Not specified	Not specified	Ecoinvent v. 3.9	ReCiPe midpoints IPCC for GWP 100	18 impact categories	- Economic revenue derived from green hydrogen and bitcoin for incremental investment in renewable energy penetration - Potential shifts in environmental burdens across freshwater ecotoxicity and marine ecotoxicity	-- (graphs only)	- LCA of multifunctional system, combining supply of renewable power for green hydrogen production and bitcoin mining - Sensitivity analysis	Alkaline	Wind Solar	NO	NO	General application: Decarbonisation coupled with crypto currency
[42]	Mio, Analysis of the energetic, economic, and environmental performance of hydrogen utilization for port logistic activities	Applied Energy	2023	Italy, Trieste	LCA no. 1 - cradle-to-gate (identifying least impactful electrolysis) LCA no. 2 - well-to-wheel (replacing diesel with hydrogen in port logistics)	LCA no. 1 - 1 kg of hydrogen produced LCA n. 2 - average port activities for 20 years	Not specified	Ecoinvent v. 3.8, attributional cut-off method	ReCiPe 2016, midpoint (H) method	18 impact categories	- GWP of green hydrogen is at least half with respect to blue hydrogen, however other impact categories are less favourable - The hydrogen compression step to 300 bar impacts on both energetic and economic performance	GWP of electrolytic hydrogen production: 4.28 kg CO ₂ eq/kg H ₂ for green alkalyne electrolysis 4.44 kg CO ₂ eq/kg H ₂ for green PEM electrolysis 5.14 kg CO ₂ eq/kg H ₂ for green solid oxide electrolysis 23.9 kg CO ₂ eq/kg H ₂ for grid-powered alkalyne electrolysis 24.4 kg CO ₂ eq/kg H ₂ for grid-powered PEM electrolysis 19.3 kg CO ₂ eq/kg H ₂ for grid-powered solid oxide electrolysis 13.5 kg CO ₂ eq/kg H ₂ for SMR hydrogen (benchmark)	- LCA based on Process Simulations - Estimate of capital and operating costs	Alkaline PEM Solid oxide	Solar, supplemented with Italian green grid electricity	Compression to 300 bar	NO	Transportation and logistics: Powering port operations (fuel cells-equipped train locomotors and trucks)
[41]	Mio, Sustainability analysis of hydrogen production processes	International Journal of Hydrogen Energy	2024	Italy, Adriatic Sea	Cradle-to-gate	1 kg of hydrogen	Not specified	Ecoinvent v. 3.8, cut-off method	ReCiPe 2016 Midpoint (H)	18 impact categories plus Energy return on energy invested (EROEI) Levelized cost of hydrogen (LCOH)	Beter environmental impact, good energetic efficiency, but higher levelised cost for green hydrogen than grey and blue hydrogen	GWP of hydrogen production: 12.6 kg CO ₂ eq/kg H ₂ for grey (SMR) hydrogen 5.27 kg CO ₂ eq/kg H ₂ for blue (SMR with CCS) hydrogen 23.5 kg CO ₂ eq/kg H ₂ for grid-powered electrolysis hydrogen [*] 4.32 kg CO ₂ eq/kg H ₂ for green hydrogen [*] [*] tabulated values in the original article appear to be inverted when compared to graph	LCA and economic analysis based on Process Simulations	Alkaline	Solar, floating	Compression to 25 bar	NO (on-site production)	Transportation, maritime: 2 trips/day of a medium-sized ferryboat across the Adriatic Sea

[74]	Palmer, Life-cycle greenhouse gas emissions and net energy assessment of large-scale hydrogen production via electrolysis and solar PV	Energy & Environmental Science	2021	China World (sensitivity analysis)	Cradle-to-gate	1 kg of dry hydrogen at 80 bar, supplied at the plant gate	Not specified	Ecoinvent v. 3.5	Not specified	GHG emissions plus Energy Return on (energy) Investment (EROI) Energy Payback Time (EPBT)	- Environmental criticalities associated with the electrolyser shutdown and the commensurate need to buffer solar electricity with storage or grid electricity - Under baseline conditions, emissions are around one-quarter of those coming from steam methane reforming	Emissions intensity of large-scale hydrogen economy: 2.3 kg CO ₂ eq/kg H ₂ for solar-battery electrolysis 4.3 kg CO ₂ eq/kg H ₂ for solar-grid powered electrolysis 8.9 (direct) to 11.9 (life cycle) kg CO ₂ eq/kg H ₂ for SMR hydrogen	- Prospective energy, cost, and environmental analysis of large-scale electrolysis plant - High-level, non-optimised design based on heuristic methods for emission assessment - Sensitivity analysis	Alkaline, large scale	Solar	Compression to 80 bar	NO	General application: Decarbonisation
[75]	Patel, Climate change performance of hydrogen production based on life cycle assessment	Green Chemistry	2024	Finland	Cradle-to-gate	1 kg of hydrogen available at the gate of the production site	Sphera GaBi v. 10.5.1.124	Gabi database 1992 to 2021	Not specified	GWP 20 GWP 100	- Production of green hydrogen using wind energy resulted in the lowest emissions (0.6 kg CO ₂ eq./kg H ₂) - Climate change impact showed a 12–25% increase for GWP-20 compared to GWP-100	GWP of hydrogen production when natural gas is sourced from Russia through (PL) route or from the U.S. through the liquefied natural gas (LNG) route: GWP 100 values: 12.3 (PL) or 14.0 (LNG) kg CO ₂ eq/kg H ₂ for grey hydrogen 7.6 (PL) or 9.3 (LNG) kg CO ₂ eq/kg H ₂ for blue hydrogen 6.1 (PL) or 8.3 (LNG) kg CO ₂ eq/kg H ₂ for turquoise hydrogen 1.6 kg CO ₂ eq/kg H ₂ for green hydrogen GWP 20 values: 13.9 (PL) or 16.5 (LNG) kg CO ₂ eq/kg H ₂ for grey hydrogen 9.4 (PL) or 11.7 (LNG) kg CO ₂ eq/kg H ₂ for blue hydrogen 8.3 (PL) or 11.5 (LNG) kg CO ₂ eq/kg H ₂ for turquoise hydrogen 1.7 kg CO ₂ eq/kg H ₂ for green hydrogen	- Infrastructure emissions not considered for turquoise hydrogen due to lack of data - Sensitivity analysis	PEM	Wind Solar	NO	NO	General application: Decarbonisation
[45]	Pawlowski, Is the Polish Solar-to-Hydrogen Pathway Green? A Carbon Footprint of AEM Electrolysis Hydrogen Based on an LCA	Energies	2023	Poland, Zarzecze	Not specified (cradle to gate)	1 kg of hydrogen produced, purity of 99.8%	SimaPro v. 8.0.5.13	Ecoinvent v. 3	IPCC for GWP 100	GWP 100	Second-best after wind power electrolysis	GWP-100 of green hydrogen production by anion exchange membrane hydrolysis powever by solar plants ("standing" or "tracker" plant): 3.01 to 4.34 (mean: 3.57) kg CO ₂ eq/kg H ₂ for standing plant 2.73 to 3.85 (mean: 3.24) kg CO ₂ eq/kg H ₂ for tracker plant	- Most of the carbon footprint related to the green hydrogen production was connected to electricity generation; - Cost analysis included	Anion exchange membrane (AEM)	Solar	NO	NO	General application: Decarbonisation
[76]	Rumayor, Perspectives for a sustainable implementation of super-green hydrogen production by photoelectrochemical technology in hard-to-abate sectors	Cleaner Production Letters	2023	Europe	Cradle-to-gate	1 MJ at 20 MPa of heat from hydrogen (120 MJ/kg)	GaBi Profession al v. 9.5	Ecoinvent v. 3.8	CML 2001	GWP Fossil abiotic depletion potential (f-ADP)	Assessment of large-scale PEC for hard-to-abate sector reveals that increased lifetime and efficiency are required	GWP of 1 MJ of compressed hydrogen produced by photoelectrochemical technologies (PEC) and benchmarks: 0.0375 kg CO ₂ eq/MJ H ₂ for renewable mix-powered PEC 0.009 kg CO ₂ eq/MJ H ₂ for solar-powered PEC 0.005 kg CO ₂ eq/MJ H ₂ for wind-powered PEC 0.0372 kg CO ₂ eq/MJ H ₂ for solar-powered water electrolysis 0.008 kg CO ₂ eq/MJ H ₂ for wind-powered water electrolysis	Ex-ante LCA	PEM (benchmark for photoelectrochemical hydrogen)	Wind Solar	Compression up to 20 MPa	NO	General application: Decarbonisation, mainly construction sector
[77]	Shamoushaki, Heat pump supply chain environmental impact reduction to improve the UK energy sustainability, resiliency and security	Scientific Reports	2023	United Kingdom	Cradle-to-gate	1 kWh of generated energy	OpenLCA v. 1.11.0	Ecoinvent v. 3.9 Environmental Footprint (EF)	ReCiPe 2016 midpoint	Carbon footprint Marine ecotoxicity Particulate matter formation Ozone depletion	The hydrogen-based heat pump leads to reduced stress on the national grid network and minimal environmental impacts associated with the supply chain	-- (graphs only)	LCA of the supply chain of different heat pumps, rather than green hydrogen	Alkaline	Not specified	NO	NO	Building heating: Hydrogen-based heat pump compared to other heating devices
[78]	Shen, Environmental and climate impacts of a large-scale deployment of green hydrogen in Europe	Energy and Climate Change	2024	European Union + United Kingdom	Not specified (cradle to use)	1 kWh fuel usage	Not specified	Not specified	Various	6 impact categories	- A large-scale green hydrogen deployment would cause a burden shift from climate and fossil resource use to human health, mineral resource use, and ecosystem damage due to the higher material consumption of the infrastructure; - Total monetized LCI cost of green hydrogen production relatively lower than that of blue hydrogen	GWP of large-scale hydrogen deployment for decarbonisation of hard-to-abate sectors	Monetized LCI cost conducted by applying monetary valuation coefficients (MVCs) based on literature data	PEM	Not specified	NO	Domestic within the EU + UK	General application: Decarbonisation of hard-to-abate sectors with (green) hydrogen as energy carrier
[51]	Sun, Climate impacts of hydrogen and methane emissions can considerably reduce the climate benefits across key hydrogen use cases and time scales	Environmental Science and Technology	2024	European Union	Well-to-use	Various, kilometre or kilogram of product	Not specified	E3 database for emissions	Not specified	GWP 20 GWP 100 Technology warming potential (TWP)	Green hydrogen not affected by methane leaks	Climate change impact of large-scale hydrogen deployment in industry under different scenarios: 52 Mt CO ₂ eq for decarbonization with green hydrogen 153 Mt CO ₂ eq for decarbonization with blue hydrogen 278 Mt CO ₂ eq for decarbonization without green hydrogen 588 Mt CO ₂ eq for no change in energy mix (benchmark)	LCA based on Hydrogen Council (2021) report "Hydrogen decarbonization pathways - A life cycle assessment" by adding hydrogen and methane emissions, and by considering multiple time horizons	Not specified	Not specified (renewables, with the alternative of using methane- or coal-based electricity)	Not specified	Not specified	General application: Decarbonisation (specific scope: accounting for gas leaks)

[79]	Terlouw, Large-scale hydrogen production via water electrolysis -- A techno-economic and environmental assessment	Energy and Environmental Science	2022	Europe, various islands: Greece, Crete; Norway, Eigerøy; Spain, Tenerife; UK, Scotland, Western Isles; Germany, Borkum	Cradle-to-gate	1 kg of hydrogen at 80 bar with a purity of more than 99.9%, considering an (average) reference flow of 10 tonnes of hydrogen production and storage per day	Brightway2	Ecoinvent v. 3.7.1, cut off method, attributional premise (python software for automated creation of prospective LCI databases from Integrated assessment models)	IPCC 2013	GWP 100a Land transformation (aggregated) Rare materials utilisation (aggregated) plus hydrogen production costs	- Producing hydrogen via water electrolysis with low costs and low GHG emissions is only possible at very specific locations nowadays - "Autonomous" configuration performs best for GHG emissions, but causes criticalities in land use and rare materials consumption	Impacts on climate change of hydrogen production in 2040 in different European locations ranging between Optimistic cost scenario: 0.4 to 0.7 kg CO ₂ eq/kg H ₂ for hybrid-green hydrogen 0.4 to 0.7 kg CO ₂ eq/kg H ₂ for hybrid hydrogen 0.7 to 1.4 kg CO ₂ eq/kg H ₂ for grid-connected hydrogen 0.9 to 1.5 kg CO ₂ eq/kg H ₂ for autonomous hydrogen 0.8 to 1.5 kg CO ₂ eq/kg H ₂ for autonomous+grid hydrogen Pessimistic cost scenario (less decarbonized grid electricity): 3.1 to 4.4 kg CO ₂ eq/kg H ₂ for hybrid-green hydrogen 3.1 to 7.6 kg CO ₂ eq/kg H ₂ for hybrid hydrogen 5.7 to 10 kg CO ₂ eq/kg H ₂ for grid-connected hydrogen 1.5 to 2.5 kg CO ₂ eq/kg H ₂ for autonomous hydrogen 1.4 to 2.5 kg CO ₂ eq/kg H ₂ for autonomous+grid hydrogen	- Prospective LCA for large-scale production of 10 tonnes of hydrogen/day - Integrated cost- and environmental analysis - Sensitivity analysis	PEM (30 bar) with water desalination using reverse osmosis	Grid-connected Hybrid Hybrid-green Autonomous Autonomous-injection*	Compression to 80 bar and storage	NO	General application: Decarbonisation
[80]	Tomos, Decarbonising international shipping	Energy Conversion and Management	2024	Global	Not specified (cradle to use)	Propulsion energy requirement for one year of global fleet operation in 2018	Sphere for Experts	Ecoinvent v. 3.7.1	ReCiPe 2016 (H)	GHG emissions	High, but not the highest, decarbonisation potential (reduction of GHG emissions with respect to heavy oil fuel)	Climate change potential of 1 year of fleet operation using alternative fuel options under various assumptions: 1.74 E+11 to 2.45 E+11 kg CO ₂ eq/year for green hydrogen 7.47 E+11 to 10.8 E+11 kg CO ₂ eq/year for blue hydrogen 0.57 E+11 to 1.39 E+11 kg CO ₂ eq/year for bio-methanol 9.36 E+11 kg CO ₂ eq/year for heavy fuel oil Various terms of comparison	- LCA of fuel usage in maritime shipping, rather than green hydrogen - Two emission allocation procedures applied for the use of captured carbon dioxide in e-methanol scenario	Not specified	Wind	Compression to unspecified (average) pressure	NO	Transportation, maritime: Propulsion of heavy shipping vessels
[62]	Vilbergsson, Can remote green hydrogen production play a key role in decarbonizing Europe in the future?	International Journal of Hydrogen Energy	2023	Iceland (electricity mix or geothermal with CCS) Austria (electricity mix) Belgium (electricity mix or wind or solar)	Cradle-to-gate	1 kg of hydrogen produced	Not specified	GaBi ts. 10.6	ReCiPe 2016 (H) midpoint	GWP excluding biogenic carbon Terrestrial Acidification (AP) plus net calorific value primary energy demand from renewable and non-renewable resources	- Lowest GHG emissions for fully green hydrogen - Liquefaction is the largest contributor to the transportation phase	Life cycle GWP of hydrogen productionin mainland Europe or in Iceland + transportation as liquid hydrogen: 0.93 kg CO ₂ eq/kg H ₂ from Iceland, geothermal in 2020 to 0.26 kg CO ₂ eq/kg H ₂ from Iceland, geothermal in 2040 22.96 kg CO ₂ eq/kg H ₂ mainland with Belgian grid in 2020 to 18.86 kg CO ₂ eq/kg H ₂ mainland with Belgian grid in 2040 Various terms of comparison	- Iceland assumed as the reference location for remote hydrogen production - Three different time points for analysis; present, 2030, and 2040 - For Belgium: intermittent renewable energy (IRES) scenarios - Sensitivity analysis - Environmental breakeven analysis for most convenient scenario (remote vs. local production)	Alkaline, 33 bar PEM, 30 bar Solid oxide, 1 bar (ambient)	Various scenarios (see geographical context in Table 3)	Liquefaction if required, depending on the scenario	From Iceland to mainland Europe through Rotterdam	General application: Decarbonisation
[81]	Weidner, Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis	International Journal of Hydrogen Energy	2023	Global	Cradle-to-use	500 Mt/yr of hydrogen produced	Activity Browser/brightway2	Ecoinvent 3.8 premise 1.0.0 (python software for automated creation of prospective LCI databases from Integrated assessment models)	- ReCiPe 2016 (H) midpoint - EF 3.0 midpoint - CML-IA baseline 4.8 from 2016 midpoint - Planetary Boundaries framework LCIA For ReCiPe 2016, EF 3.0, and CML 4.8: results normalized to the impact of the world economy with the normalization scores extracted from SimaPro 9.2.0.2 For ReCiPe2016, results converted to endpoint results (DALY)	Multiple impact categories (under 4 different LCIA methods)	- Climate change impacts of large-scale production are 3.3 to 5.4 times higher than the allocated planetary boundary, with only green hydrogen from wind energy staying below the boundary - Human health impacts and other environmental impacts are less severe in comparison but metal depletion and ecotoxicity impacts of green hydrogen deserve further attention	-- (graphs only)	- Prospective LCA based on prospective LCA datasets for 2030 and 2050 - 4 different LCIA methods focusing on burden-shifting - Calculation of priced-in environmental damages - Multiple contextualisation methods - Sensitivity analysis	Not specified, 25 bar Large scale (500 Mt/yr)	Wind Solar	NO	NO	General application: Decarbonisation of heating systems (boiler)
[82]	Weidner, Planetary boundaries assessment of deep decarbonisation options for building heating in the European Union	Energy Conversion and Management	2023	European Union + United Kingdom	Cradle-to-grave	Final heating demand of the EU + UK (monthly profile)	SimaPro v. 9.2	Ecoinvent v. 3.7	Characterisation factors related to planetary boundary categories from literature. Planetary boundaries scaled through egalitarian approach (based on population) and grandfathering or historic rights approach (based on GHG emissions)	9 planetary boundary categories	- Very low efficiency of hydrogen boilers; - Difficult delivery to non-grid connected consumers	-- (planet boundaries)	Combined assessment of technical feasibility, convenience, and environmental sustainability within the planetary boundaries	PEM	Not specified	Compression up to 250 bar	International and domestic within the EU + UK	Building heating: Replacement of fossil fuel-based heating with hydrogen as energy carrier
[83]	Winter, Mining nontraditional water sources for a distributed hydrogen economy	Environmental Science and Technology	2022	United States (USA)	Cradle-to-gate	1 kg of hydrogen	SimaPro	Ecoinvent v. 3	Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) for emissions	CO ₂ emissions for global warming	Significant contribution of hydrogen transportation to costs and emissions Water mining from nontraditional water sources for resilient and sustainable economy	Carbon intensity of green hydrogen production for varying transportation distances 5.1 to 7.7 kg CO ₂ eq/kg H ₂ (5.28 kg CO ₂ eq/kg H ₂ over 40.23 km)	Economic and environmental assessment of distributed electrolyzers using unconventional water sources	PEM, 30 bar	Wind, onshore, and solar mix (50-50)	Compression to 350 bar	Different distances to a refuelling station according to size and relative distance of distributed electrolyzers	General application: Decarbonisation of transportation

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[54]	Zhao, Life cycle assessment of H ₂ O electrolysis technologies	International Journal of Hydrogen Energy	2020	Denmark	Cradle-to-gate + treatment of decommissioned stack	1 m ² of the stack area, including non-active area of the stacks	Not specified	Ecoinvent	ReCiPe 2016 (H), midpoint	16 impact categories	Solid oxide electrolysis features the lowest GWP and mineral resource scarcity when 1 m ² of cell surface is the functional unit. However, the TRL for this technology is the lowest	Climate change associated with electrolysis stack production (calculated for 1 m ² of the stack area): 201.6 kg CO ₂ eq/m ² for alkalyne electrolysis 1765.6 kg CO ₂ eq/m ² for PEM electrolysis 109.3 kg CO ₂ eq/m ² for solid oxide electrolysis	- LCA of the electrolyser, rather than green hydrogen - Uncertainty analysis	Alkaline PEM Solid oxide	Wind	NO	NO	Renewable energy storage

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