ADVANCED SUSTAINABLE SYSTEMS
www.advsustainsys.com

Green Hydrogen and Its Supply Chain. A Critical Assessment of the Environmental Impacts

Antonella Sola, Roberto Rosa, and Anna Maria Ferrari*

Green hydrogen produced via electrolysis powered by renewables can greatly contribute to achieving carbon neutrality. The analysis of 35 papers reporting the life cycle assessment (LCA) of green hydrogen supply chains confirms the lower greenhouse gas (GHG) emissions with respect to other hydrogen forms and conventional fossil fuel and carbon systems. However, the global warming potential of green hydrogen worsens if grid electricity is used to back up renewable sources. Green hydrogen is also responsible for water consumption and for land use, while offshore platforms may be responsible for the loss of marine biodiversity. Another potential environmental hotspot is the depletion of rare metals and critical materials employed in the electrolyzer and in the power generation plants. This issue is exacerbated by the lack of information about the management of the end-of-life stage of this equipment. Notably, the delivery along the supply chain is responsible for hydrogen leaks, whose environmental consequences are still uncertain.

1. Introduction

Our society and present-day industrial systems 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 decarbonize 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 fertilizers, 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)

$$2H_2 + O_2 \rightarrow 2H_2O \quad (1)$$

A. Sola, R. Rosa, A. M. Ferrari
LCA Working Group
Department of Sciences and Methods for Engineering
University of Modena and Reggio Emilia
Via Amendola 2, Reggio Emilia 42122, Italy
E-mail: antonella.sola@unimore.it

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adsu.202400708

DOI: 10.1002/adsu.202400708

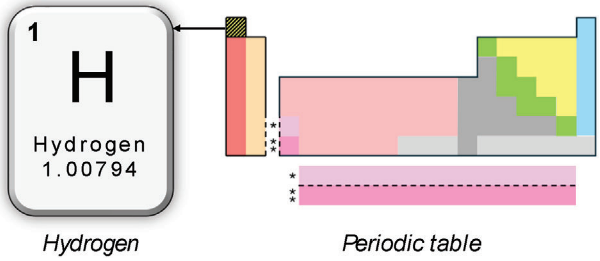

Figure 1. Hydrogen's properties as chemical element.

The enthalpy of combustion is −286 kJ mol^{-1}. 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 owing 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 electrolyzer. As a matter of fact, EIs are mainly generated by electricity when the electrolyzer 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 trigger 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] This is a standardized methodology that reliably and repeatably estimates the effects potentially caused on the environment by a given product, service or organization 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 14 040 and 14 044 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] More recently, updated guidelines for the LCA of fuel cells and hydrogen systems have been developed within the SH2E ("Sustainability Assessment of Harmonised Hydrogen Systems") project, which has been co-funded by the European Union through the Horizon 2020 initiative and by the Clean Hydrogen Partnership.[20] A first report submitted in June 2022 specifically addressed the LCA methodology to be applied to hydrogen production, hydrogen use, and hydrogen production and use systems.[21] This was followed by life cycle costing (LCC) guidelines[22] (latest version available, February 2024) and by social-life cycle assessment (S-LCA) ones[23] (latest version available, June 2023). Finally, the "SH2E guidebook for LCSA," approved after external revision in May 2024, presents the harmonized Life Cycle Sustainability Assessment (LCSA) guidelines developed within the project, which constitute a unified framework integrating the guidelines for specific life-cycle assessments.[24]

Ultimately, hydrogen is generally acknowledged as an "environmentally friendly" energy carrier. In particular, scientists and policymakers are paying much attention to the adoption of green hydrogen as a potential enabling technology towards the achievement of numerous Sustainable Development Goals[25] such as SDG 7, "Affordable and Clean Energy," SDG 13, "Climate action," and SDG 9, "Industry, Innovation and Infrastructure." However, research based on LCA has demonstrated that green hydrogen and its supply chain may actually cause a burden shift from climate change to other impact categories such as bio-geochemical flows and water use. Although the number of papers, technical reports and strategy roadmaps is growing exponentially, little attention has been paid in the literature to the objective assessment of the potential drawbacks tied to the development of a green hydrogen economy. The main purpose of the oresent review is to address this gap through the analysis of recent contributions 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). The outcomes of this investigation could facilitate the environmentally safe uptake of green hydrogen across various industries.

As exemplified in Table S1 (Supporting Information), reviews dedicated to the LCA of hydrogen are already available in archival papers and open-access materials.[8,26–42] However, just a few of them specifically revolve around green hydrogen.[8,26,29,31–34,40] The present contribution builds on these antecedents, while providing an update on the state of the art over the last 5 years, which have witnessed an exponential growth in the field.

Further to focusing on the latest trends in research, 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. This is key to identifying potential burden-shifts, as a preliminary step towards avoiding them.

Since the decarbonization of future economies and the realization of a carbon-neutral society necessitate the deployment of hydrogen at scale,[43] the present review also examines the issues that may originate from mass production of green hydrogen. Surprisingly, limited attention has been paid so far to the potential consequences of such a systemic shift.

It is envisaged that this review will thus bring a twofold 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 to make more informed decisions on future decarbonization strategies.

2. The Colors of Hydrogen

Several technologies are currently in use to produce hydrogen at scale, including chemical, biological, electrolytic, and photolytic processes.[44] 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.[45] 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,[46] 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 electrolyzer comes from renewable resources, such as solar, wind, and hydropower, as opposed to plants where power comes from nonrenewable resources such as coal or fossil fuels.

Although this convention has not been standardized, hydrogen produced with different methods is commonly described with different colors.[47] Intuitively, the darker the color, the worse the EIs caused by that hydrogen production method. In this context, the EI is commonly expressed in terms of greenhouse gas (GHG) emissions, or in terms of the global warming potential (GWP) that is associated with that hydrogen production method. For example, the main output of steam reforming from natural gas is hydrogen, but CO_2 is also generated in the process. Hydrogen produced via SMR is thus defined as “grey hydrogen” (or, sometimes, “brown hydrogen”).[48] However, if carbon capture and storage (CCS) technology is used to trap and store the CO_2 emissions, “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 colors,” with a brief explanation of the corresponding production technologies,[49] is provided in **Figure 2**.

It is estimated that 48% of hydrogen is currently obtained via SMR.[48] 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,[50] 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.[51–53] 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.

When discussing GWP values, it should be noted that, in the context of LCA, elementary flows like CO_2 or CH_4 emissions – rather than products or processes – have a GWP. For example, CO_2 has a GWP of 1, while methane (CH_4, fossil) has a GWP of around 30.[54] However, for simplicity, in the literature it is not uncommon that Authors talk about the GWP of a specific type of hydrogen or a given hydrogen-related process, actually meaning the GWP of the elementary flows which are associated with that specific type of hydrogen or that hydrogen-related process. To clarify, a practical example among many others may be offered by the contribution by Kanz et al.,[36] wherein the Authors harmonize the results of 13 LCA studies regarding solar-powered electrolysis according to a consistent framework described in their contribution and then reach the conclusion that the highest GWP calculated in their study “is over four times lower than the GWP of grid-powered electrolysis in Germany.”

The color-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 Organization, 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 CO_2e per kg H_2 taken as an average over a 12-month period).”[55] According to the European Parliament, in a Topic published in 2021 and then updated in 2023, “Clean hydrogen (“renewable hydrogen” or “green hydrogen”) is produced by the electrolysis of water using electricity from renewable sources and emits no greenhouse gases during its production.”[56]

The label “green hydrogen” may also be applied to hydrogen produced from sustainable biomass.[57] In order to obviate this ambiguity in hydrogen-related literature (both scientific and technic), intensity of CO_2 emissions and the corresponding GWP have been suggested as a potential classification parameter based on a quantitative assessment.[58] For example, the Green Hydrogen Standard for India, issued by the Ministry of New and Renewable Energy (MNRE) in August 2023, defines “Green hydrogen” as having a well-to-gate emission not exceeding 2 kg CO_2 eq/kg H_2 taken as a 12-month average. The standard applies to both electrolysis-based and biomass-based hydrogen production methods.[59,60] However, it is worth noting that, in spite of being less ambiguous than color shades, CO_2 (equivalent) emissions are just a single indicator, and only provide a partial representation of the potential impact of the hydrogen industry on the environment.

Meanwhile, the European Union is moving away from the color-based classification in favor of a production-based scheme, where “renewable hydrogen” should be considered instead of “green hydrogen.” According to the two delegated acts adopted

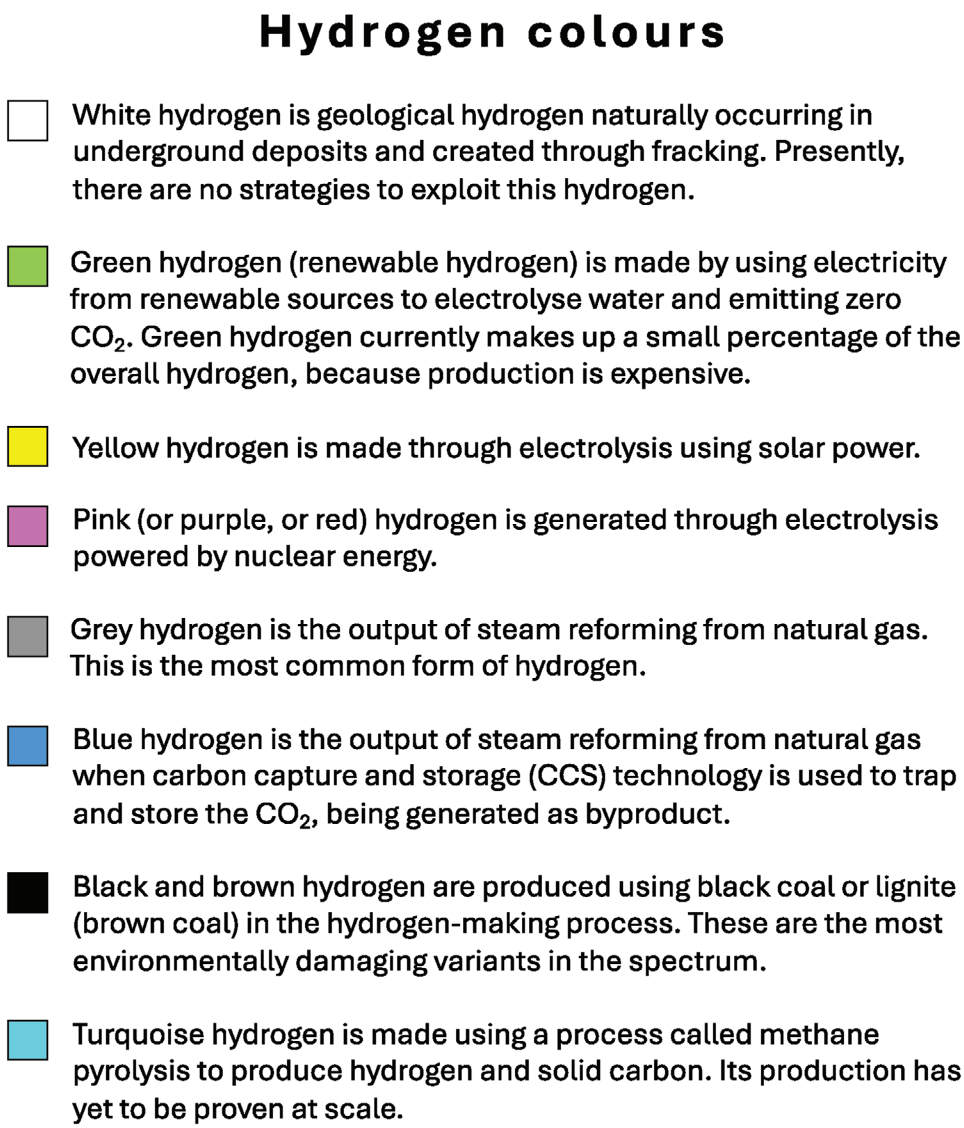

Figure 2. Common color-based nomenclature applied to hydrogen produced by different methods.

by the European Commission in June 2023 to complement the Renewable Energy Directive, "renewable hydrogen" can be obtained via electrolysis using renewable electricity to split water into hydrogen and oxygen. Further to this, renewable hydrogen should enable at least 70% GHG savings compared with fossil fuels over their entire life cycle. Accordingly, the delegated Acts set out a precise procedure for the calculation of the life-cycle emissions of renewable hydrogen (also applicable to recycled carbon fuels).[61]

3. 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.[58] 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 favor the growth of green hydrogen over other hydrogen technologies.[31,58] 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.[62–65] This approach to storing energy is generally known as "power-to-gas."[66] 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 recognize that the production of green hydrogen can also compete with existing decarbonization targets by diverging renewable

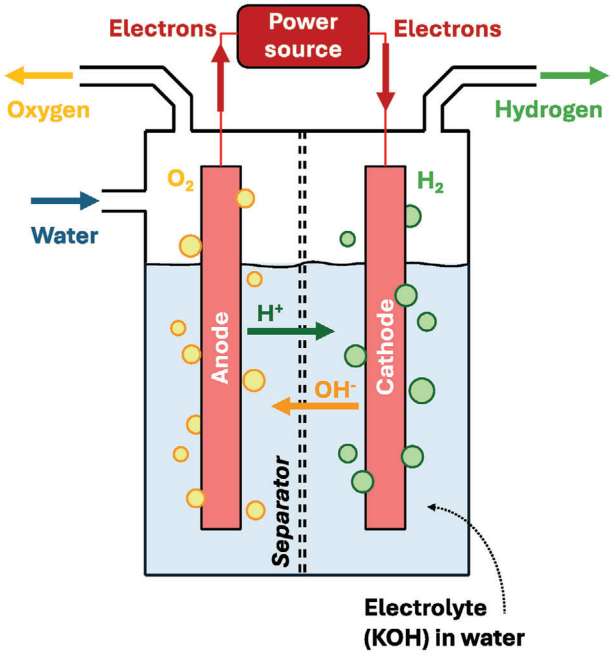

Figure 3. Schematic representation of an electrolysis cell.

electricity from the grid.[64,67] 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."[68]

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)[69]

$$2H_2O + \text{electricity}\left(237.2\ \text{kJmol}^{-1}\right) + \text{heat}\left(48.6\ \text{kJ mol}^{-1}\right) \rightarrow 2H_2 + O_2 \tag{2}$$

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%.[45]

There exist different kinds of electrolysis cells. The following sections summarize the main features of commercially available technologies. For illustrative purposes, **Figure 3** exemplifies the functioning mechanism of an alkaline electrolytic cell. Regardless of the specificities of the individual technologies, basically all electrolytic cells are comprised of four main components, namely the electrodes, including (i) the oxygen electrode (anode) where the oxygen evolution reaction occurs and (ii) the hydrogen electrode (cathode) where the hydrogen evolution reaction occurs; (iii) 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.[34]

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.[34]

Electrolytic cells can be assembled in series to build up a "stack." Neighboring cells are separated by a bipolar plate called "interconnect," and the stack is completed by an appropriate framing.[70] The electrolyzer is ultimately a collection of multiple stacks. Besides the cells, other components are needed for the electrolyzer to function as intended.[34] 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.[70,71]

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.[50,72] In the multiunit reactor configuration for catalytic methanation of flue gases described by Chirone et al.,[73] for example, an electrolyzer is exploited for producing both hydrogen and oxygen. Hydrogen is used for the purification and methanation of CO_2, 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 technologies were deployed at scale, this would oversaturate the oxygen market. As a term of comparison, according to the numbers reported by de Kleijne et al.,[68] the estimated European oxygen market for 2030 would be around 17 million tons per year, while the volume of oxygen coproduced in electrolytic processes would grow to 80 million tons per year by that time, owing to the European target of producing 10 million tons 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.[33]

3.1. Alkaline Electrolyzers

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

$$4H^+ + 4e^- \rightarrow 2H_2\ \text{(cathode)} \tag{3a}$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^-\ \text{(anode)} \tag{3b}$$

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.[74] High pressure electrolyzers bypass the postproduction 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 is nearly proportional to the installed capacity and, ultimately, to the total surface area of the electrolyzer. As a result, alkaline electrolysis is the most widespread hydrogen production technology at commercial level worldwide.[8,70]

3.2. Polymer Electrolyte Membrane (PEM) Electrolyzers

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 ≈50–100 °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 (4a). Protons move through the membrane to reach the cathode, where they are reduced closing the circuit and generating hydrogen (gas) according to Equation (4b)

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \text{ (anode)} \tag{4a}$$

$$4H^+ + 4e^- \rightarrow 2H_2 \text{ (cathode)} \tag{4b}$$

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.[75]

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.[8,70]

An emerging technology combines a PEM electrolyzer 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 radiation 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 unitized regenerative proton exchange membrane fuel cell (UR-PEMFC) or unitized regenerative fuel cell (URFC), offers additional advantages, such as a lower capital cost and a simplified architecture.[76]

3.3. Solid Oxide Electrolyzers

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.[77] 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 (5a). 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 (5b)

$$2H_2O + 4e^- \rightarrow 2H_2 + 2O^{2-} \text{ (cathode)} \tag{5a}$$

$$2O^{2-} \rightarrow O_2 + 4e^- \text{ (anode)} \tag{5b}$$

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.[78] 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.[79]

4. Literature Search: Methodology

4.1. Search Procedure

On June 12, 2024, a literature search was conducted in Scopus to identify recent contributions regarding the LCA of green hydrogen and its supply chain. Although some modifications were deemed necessary due to the different research fields, the

PRISMA statement (originally intended for clinical surveys) informed the search methodology.[80,81]

The search strings used in Scopus were "green hydrogen" in "Article title, Abstract, Keywords" and "life cycle assessment" in "Article title, Abstract, Keywords." No additional search rules were applied in Scopus. This returned 105 records, whose bibliographic details (abstract included) were exported to a text file for further analysis. Relevant contributions were initially classified based on the document type, since the survey was directed to research studies. Accordingly, reviews were not considered. In spite of being sometimes regarded as "grey literature," conference papers and proceedings were accepted, but only if the text could be found through Scopus or openly available online. Similarly, for a matter of accessibility to an international audience, only English documents were considered. In terms of content, the preselected research contributions were scrutinized for the environmental LCA of green hydrogen and its supply chain, where "green hydrogen" was meant to be 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.[82] 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. As the main stages of the life cycle of green hydrogen, production (with upstream processes), delivery, and applications were all factored in. However, research specifically addressed to the functioning and optimization of fuel cells was not included, as this was deemed a self-standing technology needing a separate analysis. Finally, only research papers published from 2019 onwards were further considered.

The screening led to the identification of 33 contributions. However, two of them were proceedings whose full text could not be retrieved. For the reasons specified above, these contributions were disregarded. Conversely, 4 additional research papers meeting the selection criteria were found through cross-referencing ("snowball effect"). Finally, this led to a reference sample of 35 research articles and proceedings (in the following, referred to as "papers").[4,43,45,50–53,58,62,64,67,68,70,71,73,78,83–101]

The outcome of the literature survey is discussed in the following section. Precise data is provided in Table S2 (Supporting Information), which lists for each selected paper: Geographical context, system boundary, functional unit, software, background database, life cycle impact analysis (LCIA) method(s), impact or damage categories calculated, main outcomes and methodological notes. Table S2 (Supporting Information) 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.

4.2. Limitations

The analysis of the literature was focused on contributions published starting from 2019 to provide an up-to-date view of the field. However, this does not automatically imply that contributions published before 2019 are outdated. In fact, many of them (although not included in the statistics presented in Section 5) have been leveraged for substantiating the discussion in the following sections. Finally, focusing the analysis on recent contributions was a methodological decision, motivated by the objective of highlighting emergent trends in the literature. Meanwhile, the numerous reviews listed in Table S1 (Supporting Information), already provide a thorough analysis of previous research.

Another potential limitation to the search methodology consists in using Scopus. This database was selected because it offers a very broad coverage, and all content is reviewed and selected by an independent Content Selection and Advisory Board.[102] However, it is worth noting that not all journals are indexed in Scopus.

In addition to methodological reasons, the absence of potentially relevant references from the selected pool in Table S2 (Supporting Information) may have been caused by the ambiguity in terminology already addressed in Section 2. Meanwhile, it is important to point out that green hydrogen is a very dynamic field of research. Consequently, repeating the same literature analysis at different times would certainly return a larger number of records.

Ultimately, it must be acknowledged that, with the procedure outlined in Section 4.1, it is not possible to pick out every single paper in the literature dealing with LCA applied to green hydrogen and its supply chain. On the other hand, this also goes beyond the scope of the present review. Rather, the selected pool of papers in Table S2 (Supporting Information) is meant to be a representative sample of the latest trends in the literature, thus providing meaningful information regarding the EIs tied to the rising green hydrogen economy.

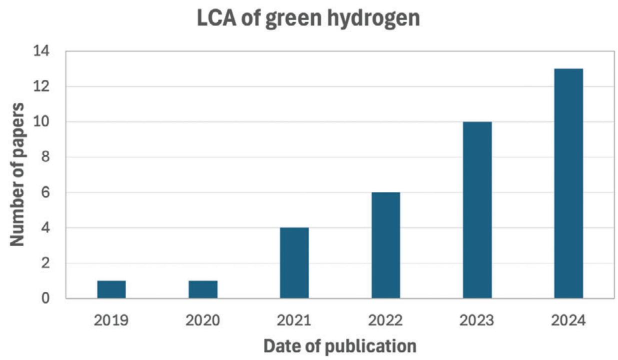

Figure 4. Time distribution of the selected research papers presenting the LCA of green hydrogen.

5. LCA Applied to the Green Hydrogen Supply Chain: State of the Art

5.1. 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 S2 in the Supporting Information), where the number of papers published in 2024 is still provisional and likely due to rise by the end of the year.

With green hydrogen being regarded as a zero-emission energy vector, the strong interest being paid to green hydrogen

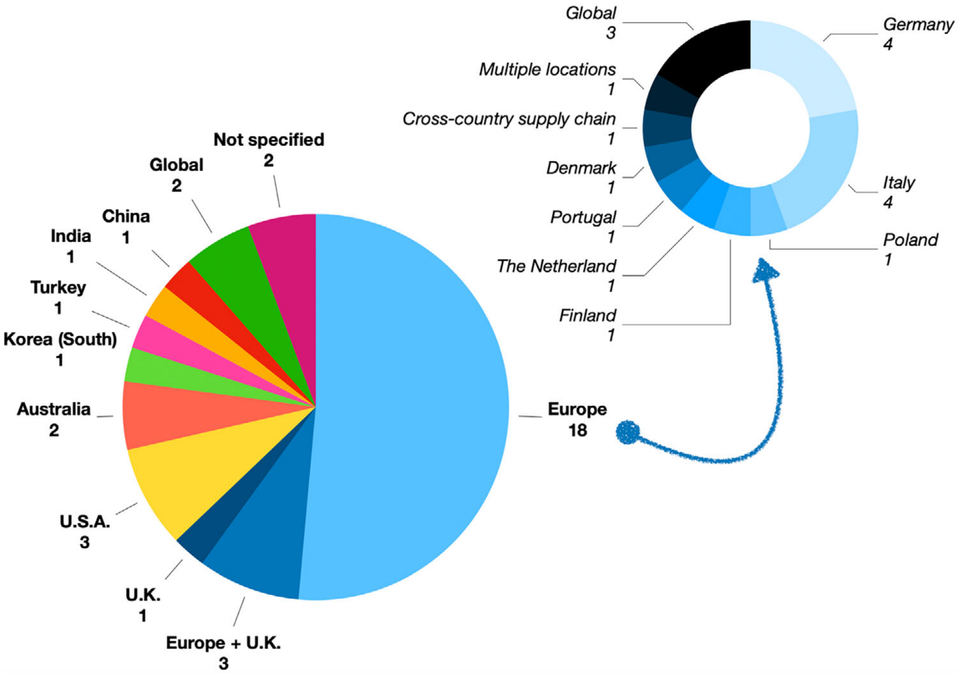

Figure 5. Geographic context of the selected research papers presenting the LCA of green hydrogen.

in the scientific community clearly reflects the push of various governments and state organizations 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.

5.2. 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 S2 in the Supporting Information), 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.

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.[103] 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.[104] Besides saving energy, the main goals of the REPowerEU Plan consist in diversifying the energy sources for the EU and incentivizing 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.[105]

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% higher than in 2021.[106] 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.

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.[107]

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.[108]

Although its role is not obvious from the data in Table S2 (Supporting Information) 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 on the LCA of green hydrogen may thus reflect a diversification of the strategies pursued in the country to reach carbon neutrality by 2060.[109]

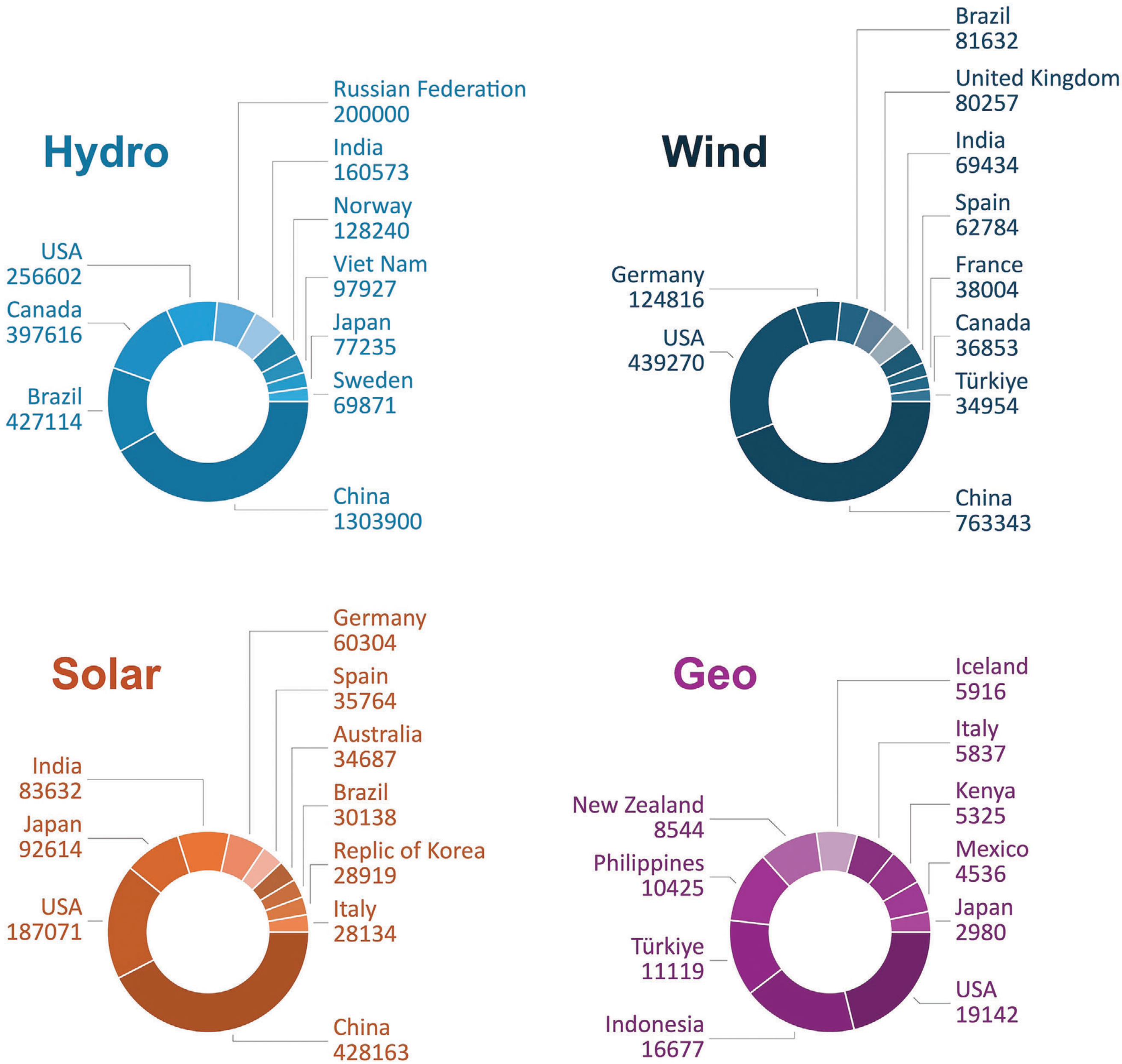

Figure 6. Top-ten country rankings based on their annual electricity generation (expressed in GWh) for different kinds of renewables. Values refer to year 2022. Data extracted from the IRENA database.[105]

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 electrolyzer. This financial hurdle is aggravated by the relatively low yield of electrolyzers. Presently, forecasts for alkaline electrolyzer installed costs in 2050 vary largely from USD 100 per kW up to USD 1200 per kW depending on the underpinning assumptions.[110] 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.

5.3. Methodological Considerations About LCA

A scrutiny of Table S2 (Supporting Information) 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 harmonizing the LCA of hydrogen production systems, "HyGuide."[17] However, looking at Table S2 (Supporting Information), 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 analyzing the production of green hydrogen in Table S2 (Supporting Information) 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.,[42] this seems to be the most practical choice, also corresponding to the HyGuide direction that "For H_2 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 S2 (Supporting Information) 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 analyze, 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.[88,100] Ultimately, the disposal or recycling of the electrolyzer, 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.[89] and one by Khan et al.[91]

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 normalized damage categories as endpoint results.[111] 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.[42] This discrepancy may be due to the different topics under examination, since the survey conducted by Wilkinson et al.[42] considers all hydrogen production technologies, and not specifically green hydrogen. Moreover, the paper by Wilkinson et al.,[42] 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.[43] that was published in 2023, but had already become available online in December 2022. The HyGuide document[17] also favored 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.[112] 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).

The guidelines developed within the SH2E project[20] could not be found in any of the reviewed research papers, likely due to the unavoidable gaps occurring between the date of release of the new recommendations, their adoption in research, and the publication of the research outcomes. However, it is worth noting that, according to the SH2E guidelines,[21] the assessment of fuel cells and hydrogen systems requires the use of the latest version of the Environmental Footprint method[19] (at the time, in 2022, version 3.0). The SH2E guidelines also specify that all impact categories are required, whilst a justification should be provided if it is decided not to include a specific impact category. Although normalization, grouping and weighting are not recommended, they can be done, provided the mid-point results are also shown, and all numbers/factors used in these calculations are openly disclosed.[21]

Finally, as detailed in the following sections, Weidner et al.[43] and Weidner and Guillén-Gosálbez[100] applied special characterization 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.

To conclude, **Figure 7** summarizes the distribution of the 35 reviewed papers based on the publication journal (details in Table S2 in the Supporting Information). Consistently with the observation of Chelvam et al.,[27] 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 analyzing the supply chain of heat pumps in Scientific Reports.[96]

6. Green Hydrogen Production

The graph in **Figure 8** (based on Table S2 in the Supporting Information) 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.

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.[42] The TRL of solid oxide electrolysis is relatively lower,

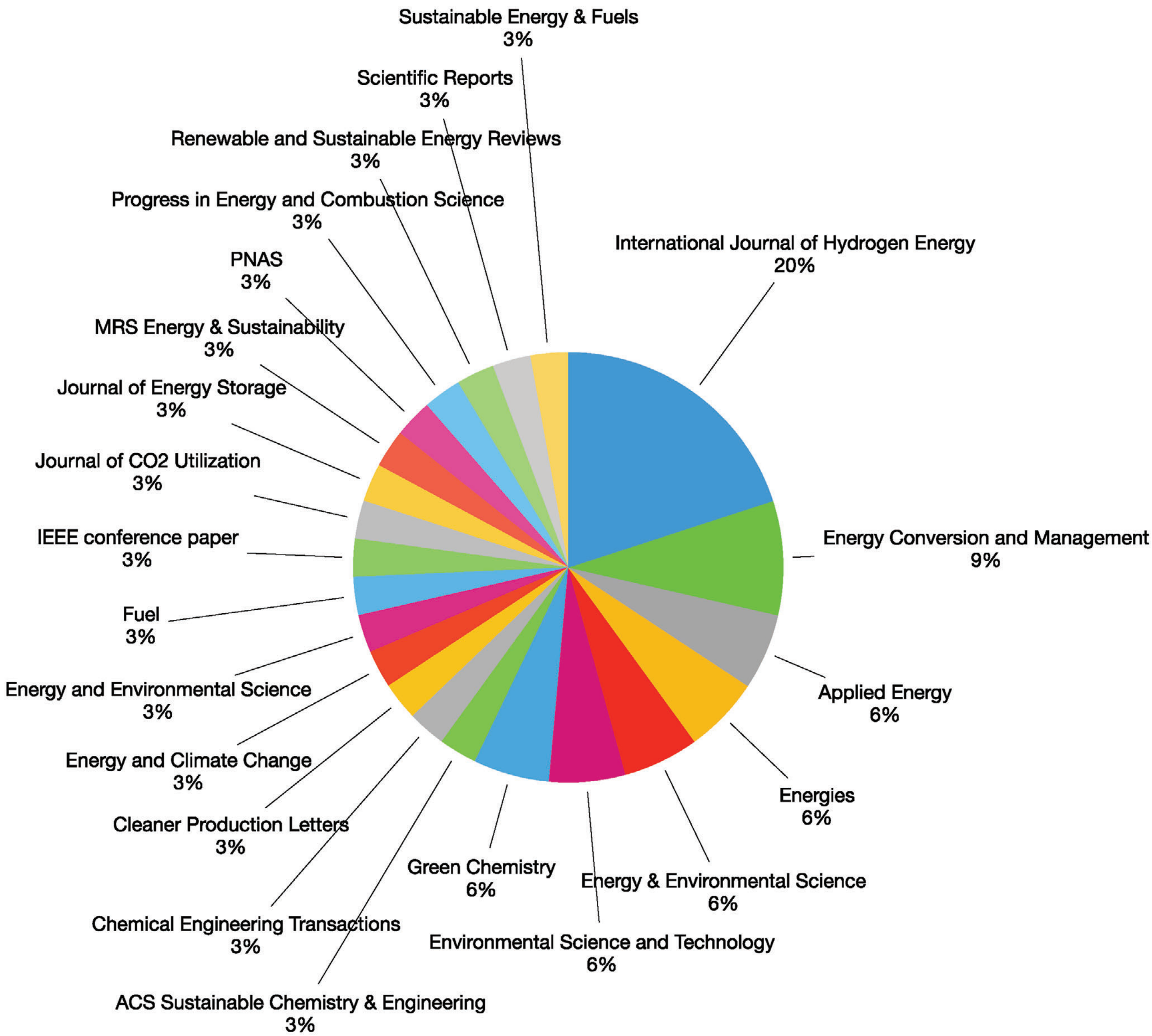

Figure 7. Publication journals of the 35 reviewed papers.

around 5,[42] which justifies the limited occurrence of this technology in the literature. Only one paper[58] analyzes 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.[42]

Patel et al.[94] systematically invstigated 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.[113] 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.,[94] 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 summarized in **Table 1**, the emissions associated with green hydrogen were the lowest and varied between 0.6 kg CO_2 eq./kg H_2 when relying upon wind energy and 2.5 kg CO_2 eq./kg H_2 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 for 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

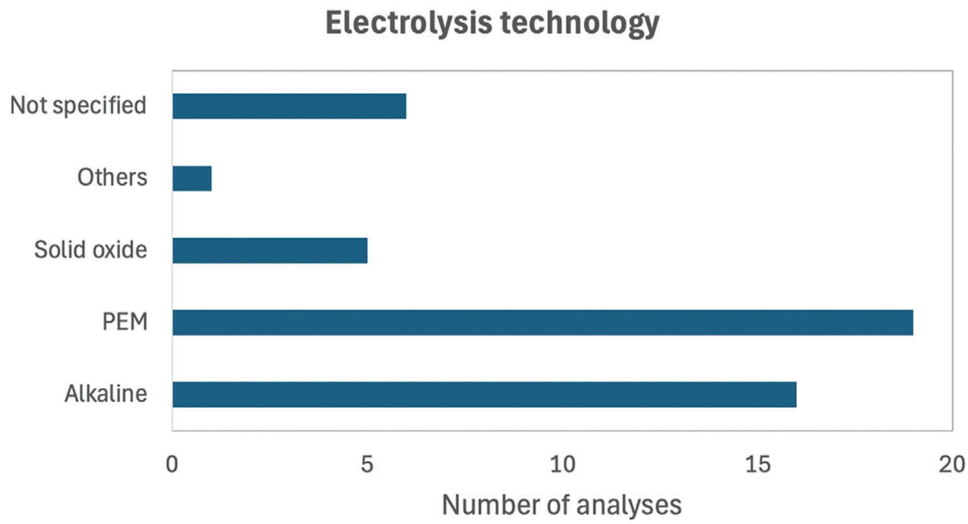

Figure 8. Number of analyses conducted in the selected papers for each kind of electrolysis technology.

instead of CO_2 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.[94] for methane-derived hydrogen were worse than previous literature data because the LCA included the extraction and transportation emissions of methane. 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.[36,114]

For solar-powered green hydrogen, Mio et al.[53] 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 need for electricity. 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 decarbonization, alkaline electrolysis was finally identified as the least impactful production pathway for green hydrogen.[53]

Zhao et al.[70] systematically compared the EIs potentially caused by the three main electrolysis technologies with a focus on the electrolyzer. Assuming the same functional unit corresponding to 1 m^2 of the electrolytic cell (including both active and nonactive surfaces), the GWP caused by the PEM stack largely exceeded the GWP of the solid oxide stack (16 times) and the alkaline stack (9 times). Similarly, the mineral resource scarcity attributable to the PEM electrolyzer was much higher than the mineral resource scarcity 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 the protective coatings on the interconnects. Furthermore, toxicity-related impacts to both human health and ecosystem resulted to be very high for all stacks.[70]

GWP and other impact categories tied to electrolytic hydrogen are strongly sensitive to the nature of the electricity being used in the electrolyzer.[71,78] For example, the comparative LCA published by Koj et al.[115] in 2018 showed that the EIs associated with hydrogen produced with an alkaline electrolyzer largely depend on the electricity supply, whose mix is different for different countries. Under the hypothesis that the same hydrogen plant is located in Spain, Austria, or Germany, it was observed that the GWP was primarily related to the use of fossil fuels for all three countries. However, the main driver for GWP was electricity generation from natural gas in Austria and Spain, as opposed to electricity generation by coal power plants in

Table 1. GWP (over 100 years, GWP-100) associated with various 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.[94]

	GWP-100 [kg CO_2 eq./kg H_2]				
Origin	Liquified methane	Gaseous methane	Wind energy	Solar energy	Wind–solar mix
Grey	13.9	12.3	–	–	–
Blue	9.3	7.6	–	–	–
Turquoise	8.3	6.1	–	–	–
Green	–	–	0.6	2.5	1.6

Germany (burning lignite and hard coal). Conversely, renewable electricity generation had a minor effect on the GWP results.

The report issued in the framework of the New Energy Externalities Development for Sustainability (NEEDS) project[116] in 2008 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,[89] 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[89] 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 could be 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.[89]

Since the electricity needed to power the electrolyzer 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 radiation.[4,117] 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.[118] 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.[87] Moreover, gases such as CO_2 and H_2S may be dissolved in the geothermal fluids, and finally released to the atmosphere. This calls for the implementation of dedicated capture and storage technologies.[119] 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,[120] 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,[68] 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.[91] As a result, the environmental burden of solar-powered electrolysis is presently the highest, and largely exceeds that of wind- and hydro-powered electrolysis, regardless of the specific electrolyzer in use.[64] However, this ranking may change when additional impact categories, and not just climate change, are accounted for, as demonstrated by Gerloff.[64] Moreover, the prospective LCA published by Weidner et al.[43] 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, electrolyzers have limited operational flexibility, and the intermittency of the power source decreases the lifespan of the electrolyzer.[78] 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 electrolyzer. However, this is likely to worsen the carbon intensity of green hydrogen depending on the specific composition of the grid mix.[50,71,78,93,98,115] 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),[121] shows the largest sources of electricity generation for some selected countries in 2023 (except for China, whose data refers to 2022). The main sources of electricity generation are obviously different in different countries.

The electricity being used to power the electrolyzer is certainly important. However, the LCA of the wind-powered electrolysis system published in the NREL report[122] suggests that the main contributor to GWP and other impact categories is the manufacture of the wind turbines, while the environmental burden associated with the electrolyzer 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).[91,93]

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.,[93] 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 neutralization technologies.[8]

As pointed out by Olindo et al.,[40] the life-cycle inventory (LCI) data on specific technologies of electricity production shows 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 electrolyzer, 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, U.S.A., and other countries 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 ≈4–8 years.[40]

Different LCIA methods consider different impact categories. As discussed by Valente,[123] HyGuide guidelines recommend the

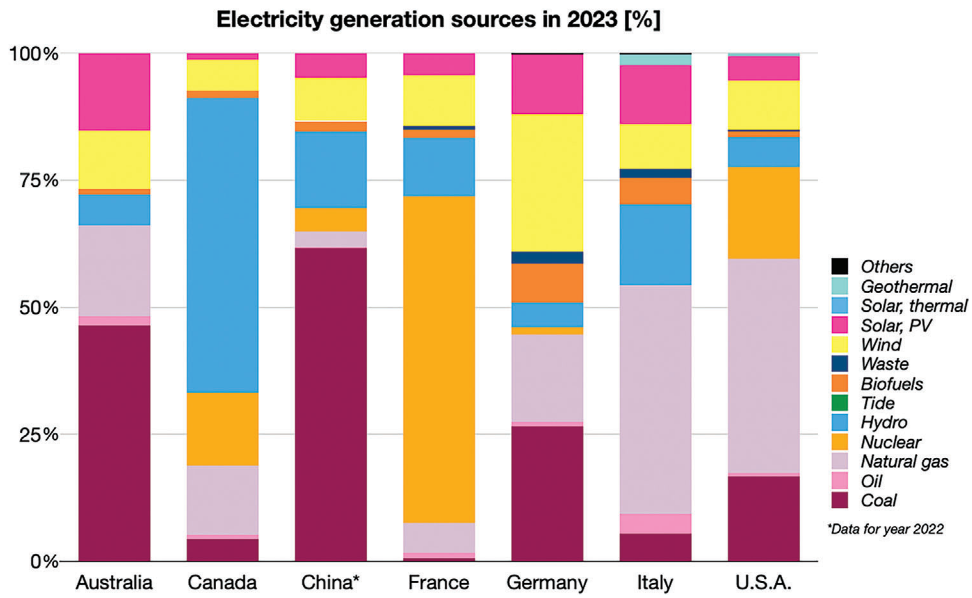

Figure 9. Largest sources of electricity generation for various countries based on IEA data for 2023 (except for China, whose data refers to 2022).[121] For comparative purposes, all values have been expressed in percent.

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 materials depletion, water consumption and land use, are less frequent. Yet, a recent contribution by Terlouw et al.[98] identified the material efficiency of the electrolyzer 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[124] or onboard a ship for the decarbonization of maritime transportation.[29] The need for critical raw materials and rare metals, such as the iridium and platinum used as catalysts in PEM electrolyzers, may also create pressure on the environment.[50,52,70,98,125]

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[126] in 2011, 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.[127] Similarly, Du et al.[128] 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 jeopardized in specific regions.[128]

As a rule of thumb, 9 kg of water are needed to produce 1 kg of H_2, while also producing 8 kg of oxygen as by-product.[68] Based on the data published in 2023 by Pawłowski et al.,[58] if all hydrogen was to be produced by electrolysis, this would result in a water requirement of 617×10^6 m^3 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 analyzed from cradle to gate,[122] the estimated total consumption of water sums up to 26.7 $kg(H_2O)/kg(H_2)$. Nearly 45% of this water is processed in the electrolyzer, 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.

7. Green Hydrogen Delivery

When analyzing 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.[78] 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 electrolyzer manufacturing capabilities and geographical areas needing hydrogen imports to satisfy their energy needs not always coincide.[78,91,129] For example, in their prospective analysis of the supply chain of hydrogen for mobility in Germany (reference year: 2032), Wulf and Kaltschmitt[130] also included

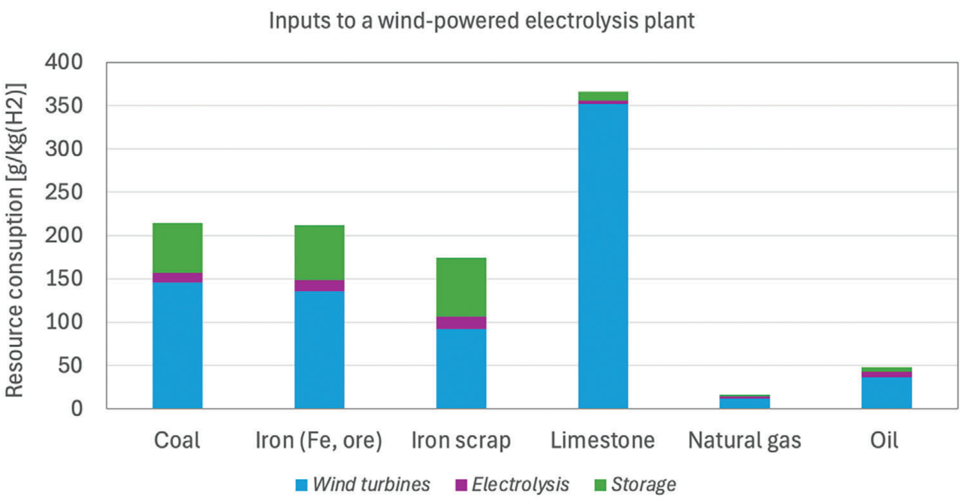

Figure 10. Main inputs (water excluded) in a wind-powered electrolysis system modelled from cradle to gate according to the data provided in the NREL report.[122] Water could not be included due to the different order of magnitude of its specific consumption.

hydrogen production by the sulphur-iodine cycle and by high-temperature electrolysis, which both required solar energy. Since solar radiation was deemed insufficient in Germany, these hydrogen production facilities were hypothetically located in Algeria. This had a non-negligible effect on the environmental impact. Specifically, hydrogen production from solar power generated, in itself, very limited impacts. Nonetheless, when the analysis was extended to also account for the long-haul transportation to Germany, the environmental performance dropped in four out of six impact categories when compared to locally-produced fossil fuel-based hydrogen. Conceivably, transportation also increased the cost of hydrogen.[130]

Akin to 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.[131] For long-range delivery, liquefied hydrogen can be transported in tanks or shipped, while compressed gaseous hydrogen can be delivered in tube trailers.[132] Alternatively, hydrogen can travel through dedicated pipelines or even mixed with methane through existing infrastructure.[133] Ammonia and other liquid organic hydrogen carriers (LOHCs) offer alternative pathways for hydrogen transportation over large commercial networks.[134] However, the hydrogen-to-carrier conversion and reconversion pose extra costs and energy requirements, and the LOHC supply chain also implies additional EIs.[83,86,135–139]

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.[84]

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.[140] 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.[140]

When analyzing the electrolytic production and delivery of hydrogen, the precise definition of the system boundaries is critical, because the impacts vary significantly whether a postproduction 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.[141] 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).[44] Similarly, liquefaction also implies significant EIs.[78] 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.[90] 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),[142] 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.[143]

8. Green Hydrogen Applications

8.1. Decarbonization of Hard-to-Abate Sectors

Hydrogen is often regarded as a viable option for the decarbonization 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 sources.[39,73,85,97,144–158]

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.[159] 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).[97,159] However, this may cause a burden shift from climate neutrality to other environmental impacts, such as material, water, and land use.[50–52]

The ability to realize the European strategy for decarbonization 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.[97] Various scale-up options were examined by Shen at al.[97] 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), decarbonization through the adoption of green hydrogen, decarbonization without green hydrogen through the adoption of blue hydrogen, and decarbonization 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 those 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 decarbonization 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.

8.2. Transportation and Mobility

With a focus on transportation, green hydrogen has been suggested as a crucial means of decarbonization of road transportation, because the emissions (per km) caused by green hydrogen vehicles are predicted to be much lower than those of conventional fuels.[89] However, it is worth noting that the future evolution of the 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.[160]

Hydrogen may be especially appealing for the decarbonization 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.,[92] 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.[92]

Green hydrogen may also be an option for fueling maritime transportation and river logistics.[161] For example, Mio et al.[52] 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 levelized cost for green hydrogen would be higher (8.76 for year 2022) than blue hydrogen (5.50).

Tomos et al.[99] adopted a modified LCA approach in order to compare the decarbonization 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), biomethanol, fatty acid methyl ester (FAME) biodiesel, and biomethane. Heavy fuel oil was assumed as a benchmark. Instead of scrutinizing 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.[99] 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 organization (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 CO_2. Notably, none of the investigated fuels was able to meet the zero-emission target that would be required for the complete decarbonization of the shipping sector. However, clean burning fuels such as biomethanol, 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 decarbonization 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.[99] 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-fueled vessels were already operational at the time, and the number was predicted to grow under the driving force of hydrogen policies and political commitment.[99]

Mio et al.[53] 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 analyzed, 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 worse results were attributed to grid hydrogen, namely hydrogen produced with conventional grid-powered electrolysis.[53]

8.3. Heating

Hydrogen has also been proposed as a decarbonization 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.[162] 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.[162] Besides the environmental concerns, building heating poses geo-political challenges due to the dependence of the EU+UK on fossil fuels,[163] 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).[164]

Famiglietti et al.[88] compared various household heating appliances, including a condensing boiler (CB), a gas heat pump (GHP), and an electric heat pump (EHP). Under the ideal hypothesis that the boiler and the gas heat pump will be fueled 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-fueled 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.[88] 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[96] comparing the supply chain of various heat pumps for the decarbonization of residential constructions in the UK. In order to tackle this conundrum, Weidner and Guillèn-Gosàlbez[100] modified the standard LCA procedure in order to verify the ability of hydrogen-based technologies and other decarbonization 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.[165] In practice, when conducting the LCA of hydrogen-based heating and other heating scenarios, Weidner and Guillèn-Gosàlbez[100] applied specific characterization factors taken from the body of literature[166,167] 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 decarbonization 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 ton of CO_2. 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-Gosàlbez,[100] decarbonization via hydrogen uptake results to be unfavorable 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 nongrid 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.

9. 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-industrialization levels.[168] However, as further discussed below, concerns are arising about the effects that a hydrogen economy may have on the environment.[28,169]

9.1. 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).[170] In other words, H_2 is an indirect GHG.[171,172]

Once released to the atmosphere, hydrogen is likely to react with OH groups to form H_2O according to Equation (6)

$$H_2 + OH \rightarrow H_2O + H \tag{6}$$

H is then likely to recombine with O_2 to form HO_2, 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.[171,172]

Meanwhile, the scarcity of OH caused by the reaction in Equation (6) would also prolong the lifetime of CH_4, which is normally regulated by Equation (7)

$$CH_4 + OH \rightarrow CH_3 + H_2O \tag{7}$$

The lifetime of CH_4 has been calculated to increase by about 1 year for every 1 ppm increase in hydrogen concentration. CH_4 is the second strongest GHG after CO_2, and extending its lifetime would further increase its radiative forcing and, hence, its GWP.[171,172]

Changes in the concentration of hydrogen are also predicted to affect atmospheric water vapor. The H_2O 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 vapor 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 vapor should also be taken into consideration in the context of the indirect climate impact of hydrogen.[171,172]

Table 2. Production-to-end use pathways originally gathered in the "Hydrogen decarbonization pathways,"[120] and then revised by Sun et al.[67] to account for hydrogen leaks.

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

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 tons of methane leak from the oil and gas supply chain every year, corresponding to around 1% of total production.[173] However, data is very uncertain,[174] and ongoing surveys indicate that leaked volumes could eventually be much bigger.[175,176] Estimates for hydrogen range from <1% to 20%, but any numbers are largely hypothetical due to the paucity of experimental evidence.[67] 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.[67] revisited the case studies originally analyzed in the "Hydrogen decarbonization pathways" (issued by the Hydrogen Council in 2021)[120] 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.[67] 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.

While most contributions on climate change only contemplate a time span of 100 years, the results published by Sun et al.[67] suggest that the decarbonization efficacy of hydrogen actually depends on time. This topic was investigated by Patel et al.[94] 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 in the short term than in 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 CO_2, 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).[177] Conversely, Patel et al.[94] 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.[94] 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.[94] 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.[94] 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.,[178] 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.[179] 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.[43] 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.[78] This transition will likely be gradual, though. Meanwhile, the decarbonization of the grid will also reduce the life cycle GHG emissions associated with other types of hydrogen, such as methane pyrolysis (turquoise) hydrogen.[50] 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.[43] The use of critical materials such as platinum-group metals (for example, in PEM electrolyzers)[70] may become both an environmental hotspot and a technological bottleneck, and this warrants the timely identification of substitution possibilities and reprocessing strategies.[45] The multi-facetted complications arising from mass-scale production may ultimately erode the environmental edge of green hydrogen over other hydrogen technologies and alternative decarbonization pathways, calling for an accurate assessment that takes into consideration multiple impact categories, and not just climate change.

9.2. Decentralized versus Centralized 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.[101] Long-range delivery of hydrogen is accompanied by leaks. Hydrogen storage requires compression or liquefaction, which are energy-intensive processes, and diesel-fueled trucks and ships for hydrogen transportation are responsible for GHG emissions. Meanwhile, electrolysis consumes a non-negligible amount of water,[180] with the recovery rate after treatment being around 50%.[101] Since water for industrial electrolysis must be pure, American Society for Testing and Materials (ASTM) Type II deionized water is the recommended quality.[181] Achieving this quality requires reverse osmosis followed by an additional polishing treatment, such as ion exchange or electro-deionization. Interestingly, as pointed out by Winter et al.,[101] 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 nonconventional 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 decentralized, small-scale electrolyzers is both technically and economically feasible. Winter et al.[101] estimated that the levelized cost of hydrogen would be minimized for production sites having a capacity in the order of 10^5 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 CO_2 emissions. Small-scale distributed electrolyzers would be even more convenient with respect to large-scale centralized plants if high CO_2 taxes ("carbon taxes") were applied, because the longer transportation distance would result in higher emissions and hence in additional penalties.[101]

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 electrolyzer capacity needs to be scaled up by orders of magnitude in order to meet the climate neutrality target by 2050.[93,182] Accordingly, Krishnan et al.[71] predicted that future electrolyzers will have larger stacks with higher current density to increase the hydrogen production rate and boost the electrolyzer 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 electrolyzer 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.[183] 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.[184] The crucial importance of critical raw materials in a future hydrogen economy is openly recognized in the LCA guidelines issued within the SH2E project for the analysis of fuel cells and hydrogen systems. Although based on European metrics for critical raw materials, the SH2E guidelines propose the formulation of a new indicator to analyze criticality. The new indicator, which takes into account the Supply Risk (SR) as defined by the European Commission, the import reliance and the recycling rate-corrected consumption of each material, should be interpreted along with the indicator "Resource use, minerals and metals" considered in the Environmental Footprint (EF, version 3.0) list of impact categories.[21]

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.[71,185]

Finally, it is worth mentioning that, at present, there are no large-scale green hydrogen plants in operation, which makes it very difficult to obtain verified primary data for LCA studies.[93] 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.[43] As accurate as they can be, these assumptions are still subject to uncertainty.[136]

9.3. Research Opportunities

Research is now being geared towards the development of new water-splitting routes.[186–189] 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 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 m^{-2} (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.,[95] standing the STH efficiency 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 m^{-2}). 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.[95]

Finally, in order to meet the United Nations' SDGs, social concerns should be taken into consideration in addition to environmental and economic ones. Although this is still an emerging area of research, as previously mentioned the SH2E program has provided a structured framework for analyzing the impacts of fuel cells and hydrogen systems through S-LCA[23] and LCSA.[24] Meanwhile, an increasing number of contributions are bringing to light social hotspots potentially associated with green hydrogen.[190] 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 electrolyzer and the renewable energy infrastructure must be sourced from various parts of the world.[127] 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.

10. Conclusions

In addition to rich information from the archival literature and numerous reports and websites, 35 research papers were analyzed to determine how life cycle assessment (LCA) has been applied to the supply chain of green hydrogen and to understand how a green hydrogen economy is predicted to affect the environment. In the absence of a standardized 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 analyzed 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 electrolyzer. 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 decarbonization initiatives.

- Further to this, electricity is needed to build the electrolyzer, 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 jeopardize 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 electrolyzer, but also the solar or wind farm or other renewable power generation plants needed to run the electrolyzer.
- Rare metals and critical materials are employed in the electrolyzer (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 electrolyzer.
- 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, especially if transport is still fossil-fuel based.
- 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.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This research was partly funded by the European Commission through the I3 Interregional Innovation Investments Program – Investments for interregional innovation, project "Hydrogen Valley in the Province of Mantova", acronym "HyMantoValley", project ID 101 115 147.

Open access publishing facilitated by Universita degli Studi di Modena e Reggio Emilia, as part of the Wiley - CRUI-CARE agreement.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A.S.: conceptualization, data curation, writing—original draft; R.R.: writing—review and editing; A.M.F.: resources, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Keywords

electrolysis, environmental impact, green hydrogen, life cycle assessment, supply chain

Received: September 17, 2024
Revised: November 6, 2024
Published online:

[1] IEA. Global electricity demand set to rise strongly this year and next, reflecting its expanding role in energy systems around the world. IEA. **2024** [cited 2024 Jul 19], https://www.iea.org.
[2] M. Huismans, F. Voswinkel Electrification – Energy System. IEA. **2023** [cited 2024 Jul 19], https://www.iea.org/energy-system/electricity/electrification.
[3] European Commission. Energy Performance of Buildings Directive. [cited 2024 Jun 10], https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.
[4] A. Lal, F. You, *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2313911121.
[5] C. Baraniuk Electricity grids creak as AI demands soar. BBC. 2024 May 21 [cited 2024 Jun 10], https://www.bbc.com/news/articles/cj5ll89dy2mo.
[6] A. S. Luccioni, Y. Jernite, E. Strubell, The 2024 ACM Conference on Fairness, Accountability, and Transparency, Rio de Janeiro (Brazil) **2024**, pp. 85.
[7] OSTP, *Climate and Energy Implications of Crypto-Assets in the United States*, White House Office of Science and Technology Policy, Washington, D.C., U.S.A **2022**.
[8] R. Bhandari, C. A. Trudewind, P. Zapp, *J. Cleaner Prod.* **2014**, *85*, 151.
[9] FCHEA, Hydrogen in industrial applications. Fuel Cell and Hydrogen Energy Association [cited 2024 Jun 10], https://www.fchea.org/hydrogen-in-industrial-applications.
[10] C. Douglas, B. Emerson, T. Lieuwen, T. Martz, R. Steele, B. Noble, *NOx Emissions from Hydrogen-Methane Fuel Blends*, Georgia Tech – Strategic Energy Institute, Atlanta, GA **2022**.
[11] S. G. Simoes, J. Catarino, A. Picado, T. F. Lopes, S. di Berardino, F. Amorim, F. Gírio, C. M. Rangel, T. Ponce de Leão, *J. Cleaner Prod.* **2021**, *315*, 128124.
[12] M. J. Pasqualetti, *Ann. Assoc. Am. Geogr.* **2011**, *101*, 907.
[13] L. Späth, *Energy Policy* **2018**, *122*, 429.
[14] R. R. Hernandez, S. B. Easter, M. L. Murphy-Mariscal, F. T. Maestre, M. Tavassoli, E. B. Allen, C. W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, M. F. Allen, *Renew. Sustain. Energy Rev.* **2014**, *29*, 766.
[15] S. Hellweg, L. Milà i Canals, *Science* **2014**, *344*, 1109.
[16] Final Report Summary – H2FC-LCA (Development of Guidance Manual for LCA application to Fuel cells and Hydrogen technologies) | FP7. CORDIS European Commission [cited 2024 Jun 11], https://cordis.europa.eu/project/id/256850/reporting.
[17] A. Lozanovski, O. Schuller, M. Faltenbacher Guidance document for performing LCA on hydrogen production systems. **2011** [cited 2024 Jun 11], https://fc-hyguide.eu/documents/10156/HY_Guidance_Document.pdf.
[18] P. Masoni, A. Zamagni Guidance document for performing LCA on fuel cells. **2011** [cited 2024 Jun 11], https://fc-hyguide.eu/documents/10156/FC_Guidance_Document.pdf.
[19] E. Commission. European Platform on LCA | EPLCA. [cited 2024 Jun 11], https://eplca.jrc.ec.europa.eu/ilcd.html.
[20] SH2E homepage, https://sh2e.eu/.
[21] E. Bargiacchi, G. Puig-Samper, F. Campo-Corriedo, D. Iribarren, J. Dufour, A. Ciroth, T. Barreiros, C. di Noi, K. Maister, P. Zapp, A. Schreiber, C. Wulf, A. Schonhoff, SH2E – D2.2 Definition of FCH-

LCA guidelines. **2022** [cited 2024 Oct 28]. Report No.: D2.2, https://sh2e.eu/downloads/.
[22] C. Wulf, P. Zapp, A. Schonhoff, E. Bargiacchi, D. Iribarren, J. Dufour, A. Ciroth, C. di Noi, Y. Ishimoto, SH2E – D4.1 Definition of FCH-LCC guidelines. 2024 [cited 2024 Oct 28]. Report No.: D4.1, https://sh2e.eu/downloads/.
[23] D. Iribarren, F. Campo-Corriedo, J. Dufour, C. di Noi, A. Ciroth, S. H. Murali, S. Springer, C. Wulf, SH2E – D4.2 Definition of FCH-SLCA guidelines. **2023** [cited 2024 Oct 28]. Report No.: D4.2, https://sh2e.eu/downloads/.
[24] M. Martín-Gamboa, F. Campo-Corriedo, D. Iribarren, J. Dufour, C. Wulf, A. Schreiber, S. K. Springer, Y. Ishimoto, M. Yuji, A. Hamed, A. Ciroth, SH2E – D5.1 SH2E guidebook for LCSA. **2024** [cited 2024 Oct 28]. Report No.: D5.1, https://sh2e.eu/downloads/.
[25] U.N., The 17 goals | Sustainable Development. [cited 2024 Oct 29], https://sdgs.un.org/goals.
[26] W. Ajeeb, R. C. Neto, P. Baptista, *Sustain. Energy Technol. Assess.* **2024**, *69*, 103923.
[27] K. Chelvam, M. M. Hanafiah, K. S. Woon, K. A. Ali, *Energy Rep.* **2024**, *11*, 369.
[28] C. L. M. Eh, A. N. T. Tiong, J. Kansedo, C. H. Lim, B. S. How, W. P. Q. Ng, *Chem. Eng. Trans.* **2022**, *94*, 1273.
[29] D. Elrhoul, M. Romero Gómez, M. Naveiro, *Int. J. Green Energy* **2023**, *20*, 1800.
[30] G. Gonzales-Calienes, M. Kannangara, J. Yang, J. Shadbahr, C. Deces-Petit, F. Bensebaa, N. Ghavidel Mehr, C. Diffo Teguia, M. Akbari, M. Benali, J. Chen, *Life Cycle Assessment of Hydrogen Production Pathways in Canada*, National Research Council of Canada, Ottawa, Ontario, Canada **2022**.
[31] A. M. Hamed, T. N. A. Tuan Kamaruddin, N. Ramli, M. F. Abdul Wahab, *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1281*, 012034.
[32] Z. Hammi, N. Labjar, M. Dalimi, Y. El Hamdouni, E. M. Lotfi, S. El Hajjaji, *Int. J. Hydrog. Energy* **2024**, *80*, 1030.
[33] N. S. Hassan, A. A. Jalil, S. Rajendran, N. F. Khusnun, M. B. Bahari, A. Johari, M. J. Kamaruddin, M. Ismail, *Int. J. Hydrog. Energy* **2024**, *52*, 420.
[34] R. K. Iyer, J. C. Kelly, A. Elgowainy, *Electrolyzers for Hydrogen Production: Solid Oxide, Alkaline, and Proton Exchange Membrane*, Argonne, USA **2022**.
[35] M. Ji, J. Wang, *Int. J. Hydrogen Energy* **2021**, *46*, 38612.
[36] O. Kanz, K. Bittkau, K. Ding, U. Rau, A. Reinders, *Front. Electron.* **2021**, *2*, 711103.
[37] M. P. Maniscalco, S. Longo, M. Cellura, G. Miccichè, M. Ferraro, *Environments* **2024**, *11*, 108.
[38] D. Melideo, R. Ortiz Cebolla, E. Weidner Ronnefeld, *Life cycle assessment of Hydrogen and Fuel Cell Technologies, EUR 29986 EN, Publications Office of the European Union*, Luxembourg, **2020**, ISBN 978-92-76-13185-4, https://doi.org/10.2760/434747, JRC116599.
[39] A. K. Mohammad, C. Sumeray, M. Richmond, J. Hinshelwood, A. Ghosh, *Aerospace* **2022**, *9*, 801.
[40] R. Olindo, N. Schmitt, J. Vogtländer, *Sustainability* **2021**, *13*, 5250.
[41] G. Puig-Samper, E. Bargiacchi, D. Iribarren, J. Dufour, *J. Clean. Prod.* **2024**, *470*, 143330.
[42] J. Wilkinson, T. Mays, M. McManus, *Clean. Environ. Syst.* **2023**, *9*, 100116.
[43] T. Weidner, V. Tulus, G. Guillén-Gosálbez, *Int. J. Hydrogen Energy* **2023**, *48*, 8310.
[44] F. Li, D. Liu, K. Sun, S. Yang, F. Peng, K. Zhang, G. Guo, Y. Si, *Sustainability* **2024**, *16*, 1890.
[45] K. Bareiß, C. De La Rua, M. Möckl, T. Hamacher, *Appl. Energy* **2019**, *237*, 862.
[46] A. T-Raissi *Water splitting: Thermochemical*, In: R.A. Scott (Ed.), Encyclopedia of Inorganic and Bioinorganic Chemistry, https://doi.org/10.1002/9781119951438.eibc0463.
[47] W. Liu, Y. Wan, Y. Xiong, P. Gao, *Int. J. Hydrogen Energy* **2022**, *47*, 24584.
[48] A. Lal, F. You, *AIChE J.* **2023**, *69*, e17956.
[49] National Grid Group, The hydrogen colour spectrum. [cited 2024 Jun 11], https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum.
[50] M. Hermesmann, T. E. Müller, *Prog. Energy Combust. Sci.* **2022**, *90*, 100996.
[51] E. Barbera, A. Mio, A. Massi Pavam, A. Bertucco, M. Fermeglia, *Chem. Eng. Trans.* **2022**, *96*, 109.
[52] A. Mio, E. Barbera, A. Massi Pavan, A. Bertucco, M. Fermeglia, *Int. J. Hydrogen Energy* **2024**, *54*, 540.
[53] A. Mio, E. Barbera, A. M. Pavan, R. Danielis, A. Bertucco, M. Fermeglia, *Appl. Energy* **2023**, *347*, 121431.
[54] IPCC – Greenhouse Gas Protocol. IPCC Global Warming Potential Values. [cited 2024 Oct 28], https://ghgprotocol.org/sites/default/files/2024-08/Global-Warming-Potential-Values%20%28August%202024%29.pdf.
[55] GH2. The GH2 Green Hydrogen Standard | Green Hydrogen Organisation. [cited 2024 Jun 25], http://gh2.org/our-initiatives/gh2-green-hydrogen-standard.
[56] Renewable hydrogen: What are the benefits for the EU? Top. Eur. Parliam. **2021** [cited 2024 Oct 29], https://www.europarl.europa.eu/topics/en/article/20210512STO04004/renewable-hydrogen-what-are-the-benefits-for-the-eu.
[57] A. P. Damiri, E. Stamatakis, S. Bellas, M. Zoulias, G. Mitkidis, A. G. Anastasiadis, S. Karellas, G. Tzamalis, A. Stubos, T. Tsoutsos, *Hydrogen* **2024**, *5*, 163.
[58] A. Pawłowski, A. Żelazna, J. Żak, *Energies* **2023**, *16*, 3702.
[59] MNRE. Green Hydrogen Standard for India. [cited 2024 Oct 29], https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/aug/doc2023819241201.pdf.
[60] India announces definition of Green Hydrogen. [cited 2024 Oct 29], https://pib.gov.in/pib.gov.in/Pressreleaseshare.aspx?PRID=1950421.
[61] European Commission. Hydrogen. [cited 2024 Oct 29], https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en.
[62] S. Das, S. De, R. Dutta, S. De, *Renew. Sustain. Energy Rev.* **2024**, *191*, 114135.
[63] FCHEA. Hydrogen as storage. Fuel Cell and Hydrogen Energy Association [cited 2024 Jun 20], https://www.fchea.org/hydrogen-as-storage.
[64] N. Gerloff, *MRS Energy Sustain.* **2023**, *10*, 174.
[65] M. Hirscher, V. A. Yartys, M. Baricco, J. Bellosta von Colbe, D. Blanchard, R. C. Bowman, D. P. Broom, C. E. Buckley, F. Chang, P. Chen, Y. W. Cho, J.-C. Crivello, F. Cuevas, W. I. F. David, P. E. de Jongh, R. V. Denys, M. Dornheim, M. Felderhoff, Y. Filinchuk, G. E. Froudakis, D. M. Grant, E. MacA Gray, B. C. Hauback, T. He, T. D. Humphries, T. R. Jensen, S. Kim, Y. Kojima, M. Latroche, H.-W. Li, et al., *J. Alloys Compd.* **2020**, *827*, 153548.
[66] R. Tichler, S. Bauer, *in Storing Energy* (Ed.: T. M. Letcher), Elsevier, Oxford **2016**, pp. 373–389.
[67] T. Sun, E. Shrestha, S. P. Hamburg, R. Kupers, I. B. Ocko, *Environ. Sci. Technol.* **2024**, *58*, 5299.
[68] K. de Kleijne, H. de Coninck, R. van Zelm, M. A. J. Huijbregts, S. V. Hanssen, *Energy Fuels* **2022**, *6*, 4383.
[69] S. S. Kumar, H. Lim, *Energy Rep.* **2022**, *8*, 13793.
[70] G. Zhao, M. R. Kraglund, H. L. Frandsen, A. C. Wulff, S. H. Jensen, M. Chen, C. R. Graves, *Int. J. Hydrogen Energy* **2020**, *45*, 23765.
[71] S. Krishnan, B. Corona, G. J. Kramer, M. Junginger, V. Koning, *Int. J. Hydrogen Energy* **2024**, *55*, 26.

[72] Berenschot, Oxygen synergy for hydrogen production. **2019** [cited 2024 Dec 6], https://projecten.topsectorenergie.nl/storage/app/uploads/public/5e9/47d/800/5e947d8007aed241013086.pdf.
[73] R. Chirone, A. Paulillo, A. Coppola, F. Scala, *Fuel* **2022**, *328*, 125255.
[74] J. C. Koj, A. Schreiber, P. Zapp, P. Marcuello, *Conf. Appl. Energy ICAE2015* **2015**, *75*, 2871.
[75] F. Barbir, *Sol. Hydrogen* **2005**, *78*, 661.
[76] T. M. Gulotta, R. Salomone, F. Lanuzza, G. Saija, G. Mondello, G. Ioppolo, *Environ. Impact Assess. Rev.* **2022**, *92*, 106698.
[77] M. Mueller, M. Klinsmann, U. Sauter, J.-C. Njodzefon, A. Weber, *Chem. Ing. Tech.* **2024**, *96*, 143.
[78] K. V. Vilbergsson, K. Dillman, N. Emami, E. J. Ásbjörnsson, J. Heinonen, D. C. Finger, *Int. J. Hydrogen Energy* **2023**, *48*, 17711.
[79] Y. Wang, W. Li, L. Ma, W. Li, X. Liu, *J. Mater. Sci. Technol.* **2020**, *55*, 35.
[80] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, D. Moher, *BMJ* **2021**, *372*, n71.
[81] M. J. Page, D. Moher, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, J. E. McKenzie, *BMJ* **2021**, *372*, n160.
[82] IAEA, *Hydrogen Production Using Nuclear Energy, IAEA*, International Atomic Energy Agency, Vienna **2012**.
[83] M. S. Akhtar, R. Dickson, H. Niaz, D. W. Hwang, J. J. Liu, *Green Chem.* **2021**, *23*, 9625.
[84] M. S. Akhtar, R. Dickson, J. J. Liu, A. C. S. Sustain, *Chem. Eng.* **2021**, *9*, 17152.
[85] M. Bacatelo, F. Capucha, P. Ferrão, F. Margarido, J. Bordado, *J. CO2 Util.* **2024**, *83*, 102774.
[86] R. K. Balaji, F. You, *Energy Environ. Sci.* **2024**, *10*, 1039.
[87] A. Chidire, C. Schifflechner, T. Massier, *2023 IEEE PES Innovative Smart Grid Technologies – Asia (ISGT Asia)*, IEEE, Auckland, New Zealand **2023**, pp. 1–5.
[88] J. Famiglietti, T. Toppi, D. Bonalumi, M. Motta, *Energy Convers. Manage.* **2023**, *276*, 116527.
[89] N. Gerloff, *J. Energy Storage* **2021**, *43*, 102759.
[90] D. Guven, *Int. J. Hydrogen Energy* **2024**, *72*, 661.
[91] M. H. A. Khan, T. Sitaraman, N. Haque, G. Leslie, S. Saydam, R. Daiyan, R. Amal, S. Kara, *Int. J. Hydrogen Energy* **2024**, *62*, 769.
[92] M. Kolahchian Tabrizi, T. Cerri, D. Bonalumi, T. Lucchini, M. Brenna, *Energies* **2024**, *17*, 996.
[93] G. Palmer, A. Roberts, A. Hoadley, R. Dargaville, D. Honnery, *Energy Environ. Sci.* **2021**, *14*, 5113.
[94] G. H. Patel, J. Havukainen, M. Horttanainen, R. Soukka, M. Tuomaala, *Green Chem.* **2024**, *26*, 992.
[95] M. Rumayor, J. Fernández-González, A. Domínguez-Ramos, A. Irabien, *Clean. Prod. Lett.* **2023**, *4*, 100041.
[96] M. Shamoushaki, S. C. L. Koh, *Sci. Rep.* **2023**, *13*, 20633.
[97] H. Shen, P. Crespo Del Granado, R. S. Jorge, K. Löffler, *Energy Clim. Change* **2024**, *5*, 100133.
[98] T. Terlouw, C. Bauer, R. McKenna, M. Mazzotti, *Energy Environ. Sci.* **2022**, *15*, 3583.
[99] B. A. D. Tomos, L. Stamford, A. Welfle, A. Larkin, *Energy Convers. Manage.* **2024**, *299*, 117848.
[100] T. Weidner, G. Guillén-Gosálbez, *Energy Convers. Manage.* **2023**, *278*, 116602.
[101] L. R. Winter, N. J. Cooper, B. Lee, S. K. Patel, L. Wang, M. Elimelech, *Environ. Sci. Technol.* **2022**, *56*, 10577.
[102] Scopus content, Elsevier (**2024**). www.elsevier.com. [cited 2024 Oct 30], https://www.elsevier.com/products/scopus/content.
[103] The European Green Deal – European Commission. **2021** [cited 2024 Jul 17], https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
[104] REPowerEU. **2022** [cited 2024 Jul 17], https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en.
[105] Country Rankings. [cited 2024 Jul 18], https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/Country-Rankings.
[106] Renewable energy statistics. [cited 2024 Jul 18], https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics.
[107] J. Gabbatiss The Carbon Brief Profile: United States. Carbon Brief. 2021 [cited 2024 Jul 18], https://www.carbonbrief.org/the-carbon-brief-profile-united-states/.
[108] AKBC. Mapping the Australia-Korea hydrogen intersections. Australia-Korea Business Council **2021** [cited 2024 Jul 18], https://www.hydrogenforum.com.au/sites/hydrogenforum.com.au/files/AKBC_Mapping-the-Australia-Korea-Hydrogen-Intersections-Report_Digital.pdf.
[109] H. Liu, S. Evans, Z. Zhang, et al., The Carbon Brief Profile: China Carbon Brief. **2023** [cited 2024 Jul 18], https://interactive.carbonbrief.org.
[110] A. Navarrete, Y. Zhou The price of green hydrogen: How and why we estimate future production costs. Int. Counc. Clean Transp. **2024** [cited 2024 Jul 18], https://theicct.org/the-price-of-green-hydrogen-estimate-future-production-costs-may24/.
[111] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, R. van Zelm, *Int. J. Life Cycle Assess.* **2017**, *22*, 138.
[112] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Veronesi, M. D. M. Vieira, A. Hollander, M. Zijp, R. van Zelm, *ReCiPe 2016 – A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization*, National Institute for Public Health and the Environment, Bilthoven, The Netherlands **2016**.
[113] J. Diab, L. Fulcheri, V. Hessel, V. Rohani, M. Frenklach, *Int. J. Hydrogen Energy* **2022**, *47*, 25831.
[114] P. Balcombe, J. Speirs, E. Johnson, J. Martin, N. Brandon, A. Hawkes, *Renew. Sustain. Energy Rev.* **2018**, *91*, 1077.
[115] J. C. Koj, C. Wulf, A. Schreiber, P. Zapp, *Energies* **2017**, *10*, 860.
[116] NEEDS, Generation, of the energy carrier hydrogen – In context with electricity buffering generation through fuel cells. Icelandic New Energy; **2008** [cited 2024 Jun 13], https://www.yumpu.com/en/document/read/46449402/generation-of-the-energy-carrier-hydrogen-in-context-needs.
[117] L. Al-Ghussain, M. Alrbai, S. Al-Dahidi, Z. Lu, *Energy Convers. Manage.* **2024**, *311*, 118514.
[118] S. Kumar, E. Arzaghi, T. Baalisampang, M. M. Abaei, V. Garaniya, R. Abbassi, *Sustain. Prod. Consum.* **2024**, *46*, 655.
[119] M. R. Karlsdottir, J. Heinonen, H. Palsson, O. P. Palsson, *Geothermics* **2020**, *84*, 101727.
[120] Hydrogen Council, *Hydrogen decarbonization pathways – A life cycle assessment*, Hydrogen Council **2021**.
[121] IEA, Countries & Regions.
[122] P. L. Spath, M. K. Mann, *Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis: Milestone Completion Report*, National Renewable Energy Laboratory (NREL), Golden, CO (USA) **2004**.
[123] A. Valente, D. Iribarren, J. Dufour, *Int. J. Life Cycle Assess.* **2017**, *22*, 346.

[124] E. Cetinkaya, I. Dincer, G. F. Naterer, *Int. J. Hydrogen Energy* **2012**, *37*, 2071.
[125] J. Gerhardt-Mörsdorf, J. Incer-Valverde, T. Morosuk, C. Minke, *Energy* **2024**, *299*, 131553.
[126] A. Simons, C. Bauer, in *Transition to Hydrogen: Pathways toward Clean Transportation* (Eds.: A. Wokaun, Ed., E. Wilhelm), Cambridge University Press, Cambridge **2011**, pp. 13–57.
[127] M. S. Akhtar, H. Khan, J. J. Liu, J. Na, *J. Clean. Prod.* **2023**, *395*, 136438.
[128] L. Du, Y. Yang, X. Bai, S. Xu, L. Lin, M. Liu, *Sci. Total Environ.* **2024**, *940*, 173589.
[129] IRENA, *Geopolitics of the Energy Transformation: The Hydrogen Factor*, International Renewable Energy Agency, Abu Dhabi **2022**.
[130] C. Wulf, M. Kaltschmitt, *Sustainability* **2018**, *10*, 1699.
[131] J. A. Riera, R. M. Lima, O. M. Knio, *Int. J. Hydrog. Energy* **2023**, *48*, 13731.
[132] US Department of Energy, Office of Energy Efficiency & Renewable Energy. Hydrogen delivery. Energy.gov. [cited 2024 Jul 9], https://www.energy.gov/eere/fuelcells/hydrogen-delivery.
[133] K. Topolski, E. Reznicek, B. Erdener, et al. Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology. 2022 [cited 2024 Jul 9]. p. NREL/TP-5400-81704, 1893355, MainId:82477. Report No.: NREL/TP-5400-81704, 1893355, MainId:82477, https://www.osti.gov/servlets/purl/1893355/.
[134] M. Weikl, A. Peschel, *Curr. Opin. Green Sustain. Chem.* **2023**, *44*, 100843.
[135] M. S. Akhtar, J. Liu, *Life Cycle Assessment of Hydrogen Production from Imported Green Ammonia: A Korea Case Study* (Eds.: M. Türkay, R. Gani), Computer Aided Chemical Engineering, Vol. 50, Elsevier **2021**, 147–152.
[136] A. Arrigoni, E. Weidner, F. Dolci, R. O. Cebolla, U. Eynard, F. Mathieux. Reduction of hydrogen carbon footprint in Europe via international shipping, WHEC 2022, 23rd World Hydrogee Energy Conference, June 26–30, **2022**, Istanbul, Turkey.
[137] C. Kim, Y. Lee, H. Lee, U. Lee, K. Kim, *Energy Convers. Manag.* **2023**, *291*, 117302.
[138] J. Osorio-Tejada, N. N. Tran, V. Hessel, *Sci. Total Environ.* **2022**, *826*, 154162.
[139] S. Yun, J. Im, J. Kim, H. Cho, J. Lee, *Chem. Eng. J.* **2024**, *491*, 151875.
[140] R. Ortiz Cebolla, F. Dolci, E. Weidner Ronnefeld, Assessment of hydrogen delivery options, EUR 31199 EN, Publications Office of the European Union, Luxembourg, **2022**, ISBN 978-92-76-56421-8, https://doi.org/10.2760/869085, JRC130442.
[141] R. Hren, A. Vujanović, Y. Van Fan, J. J. Klemeš, D. Krajnc, L. Čuček, *Renew. Sustain. Energy Rev.* **2023**, *173*, 113113.
[142] U. S. Department of Energy, Office of Energy Efficiency & Renewable Energy. Hydrogen storage. Energy.gov. [cited 2024 Jul 5], https://www.energy.gov/eere/fuelcells/hydrogen-storage.
[143] J. Liu, M. Zhao, L. Rong, *Clean Energy* **2023**, *7*, 99.
[144] Y. Guo, L. Peng, J. Tian, D. L. Mauzerall, *Nat. Commun.* **2023**, *14*, 8104.
[145] H. Heidary, K. Janda, *J. Sci. Eng.* **2024**, *49*, 1855.
[146] R. S. Kadam, G. D. Yadav, *J. Clean. Prod.* **2024**, *449*, 141620.
[147] H. Kim, C. Choe, A. Lee, H. Lim, *Int. J. Hydrogen Energy* **2023**, *48*, 16148.
[148] A. Lozanovski, N. Whitehouse, N. Ko, S. Whitehouse, *Sustainability* **2018**, *10*, 1480.
[149] S. Maimaiti, Y. Gu, Q. Chen, Z. Tang, *J. Clean. Prod.* **2023**, *425*, 139002.
[150] M. R. Pratama, R. Muthia, W. W. Purwanto, *Carbon Neutrality* **2023**, *2*, 26.
[151] K. Ren, T. Zhang, X. Tan, Y. Zhai, Y. Bai, X. Shen, Y. Jia, J. Hong, *J. Clean. Prod.* **2021**, *328*, 129658.
[152] D. I. Rinawati, A. R. Keeley, S. Takeda, S. Managi, *Front. Sustain.* **2022**, *3*, 920876.
[153] D. I. Rinawati, A. R. Keeley, S. Takeda, S. Managi, *Prog. Energy* **2022**, *4*, 012001.
[154] S. Sollai, A. Porcu, V. Tola, F. Ferrara, A. Pettinau, *J. CO2 Util.* **2023**, *68*, 102345.
[155] A. M. Souza, R. V. Ribeiro, L. D. Oliveira, A. P. Alves da Silva, *J. Mater. Res. Technol.* **2023**, *24*, 7153.
[156] S. B. Walker, M. Fowler, L. Ahmadi, *J. Energy Storage* **2015**, *4*, 62.
[157] J. Zhang, R. Liu, G. Zhang, W. Zhang, J. Wang, F. Wang, *J. Clean. Prod.* **2024**, *434*, 139841.
[158] Y. Zhao, Q. Liu, Y. Duan, Y. Zhang, Y. Huang, L. Shi, J. Wang, Q. Yi, *Energy Convers. Manage.* **2022**, *268*, 115992.
[159] A. Wang, J. Jens, D. Mavins, M. Moultak, M. Schimmel, K. van der Leun, D. Peters, M. Buseman, *European Hydrogen Backbone_Analysing the future demand, supply, and transport of hydrogen, Creos, DESFA, Elering, Enagás, Energinet, Eustream, FGSZ, Fluxys Belgium, Gas Connect Austria, Gasgrid Finland, Gasunie, Gaz-System, Gas Networks Ireland, GRTgaz, National Grid, NET4GAS*, Nordion Energi, OGE, ONTRAS, Plinovodi, Snam, TAG, Teréga **2021**
[160] S. Wolff, M. Seidenfus, M. Brönner, M. Lienkamp, *J. Clean. Prod.* **2021**, *318*, 128505.
[161] X. Yan, Y. He, A. Fan, *Renew. Sustain. Energy Rev.* **2023**, *173*, 113068.
[162] EPHA, The impact of residential heating and cooking on air quality in Europe – Position paper. European Public Health Alliance (EPHA); 2022 [cited 2024 Jun 20], https://epha.org/wp-content/uploads/2022/03/epha-position-paper-clean-heating.pdf.
[163] Eurostat. Energy statistics – an overview. [cited 2024 Jun 20], https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview.
[164] Eurostat. EU imports of energy products – latest developments. [cited 2024 Jun 20], https://ec.europa.eu/eurostat/statistics-explained/index.php?title=EU_imports_of_energy_products_-_latest_developments.
[165] J. Rockström, W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, J. A. Foley, *Nature* **2009**, *461*, 472.
[166] Á. Galán-Martín, V. Tulus, I. Díaz, C. Pozo, J. Pérez-Ramírez, G. Guillén-Gosálbez, *One Earth* **2021**, *4*, 565.
[167] M. W. Ryberg, M. Owsianiak, K. Richardson, M. Z. Hauschild, *Ecol. Indic.* **2018**, *88*, 250.
[168] FCH. Hydorgen roadmap Europe. FCH – Fuel Cells and Hydrogen 2 Joint Undertaking, Now known as Clean Hydrogen Joint Undertaking; **2016** [cited 2024 Jun 4], https://data.europa.eu/doi/10.2843/341510.
[169] A. Arrigoni, L. Bravo Diaz, Hydrogen emissions from a hydrogen economy and their potential global warming impact, EUR 31188 EN, Publications Office of the European Union, Luxembourg, **2022**, ISBN 978-92-76-55848-4, https://doi.org/10.2760/065589, JRC130362.
[170] United States Environmental Protection Agency (U.S. E.P.A.). Climate Change Indicators: Climate Forcing. **2016** [cited 2024 Jul 22], https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing.
[171] N. Warwick, P. Griffiths, A. Archibald, J. Pyle, S. Keith, Atmospheric implications of increased hydrogen use. UK Government; **2022** [cited 2024 May 23], https://www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use.
[172] N. J. Warwick, A. T. Archibald, P. T. Griffiths, J. Keeble, F. M. O'Connor, J. A. Pyle, K. P. Shine, *Atmos. Chem. Phys.* **2023**, *23*, 13451.

[173] United States Environmental Protection Agency (U.S. E.P.A.), Inventory of U.S. greenhouse gas emissions and sinks (1990-2021). EPA **2023** [cited 2024 Jul 19], https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.
[174] MIT, How much does natural gas contribute to climate change through CO2 emissions when the fuel is burned, and how much through methane leaks? | MIT Climate Portal.. Massachussets Institute of Technology. [cited 2024 Dec 6], https://climate.mit.edu/ask-mit/how-much-does-natural-gas-contribute-climate-change-through-co2-emissions-when-fuel-burned#:(:text=At%20this%20rate%2C%20methane%20leaks,emissions%20for%20the%20other%2090%25.
[175] Y. Chen, E. D. Sherwin, E. S. F. Berman, B. B. Jones, M. P. Gordon, E. B. Wetherley, E. A. Kort, A. R. Brandt, *Environ. Sci. Technol.* **2022**, *56*, 4317.
[176] X. Lu, D. J. Jacob, Y. Zhang, L. Shen, M. P. Sulprizio, J. D. Maasakkers, D. J. Varon, Z. Qu, Z. Chen, B. Hmiel, R. J. Parker, H. Boesch, H. Wang, C. He, S. Fan, *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2217900120.
[177] United States Environmental Protection Agency (U.S. E.P.A.), Understanding global warming potentials. EPA. **2016** [cited 2024 Dec 6], https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.
[178] R. A. Alvarez, S. W. Pacala, J. J. Winebrake, W. L. Chameides, S. P. Hamburg, *Science* **2012**, *109*, 6435.
[179] S. Cucurachi, C. van der Giesen, J. Guinée, *Cph. Den.* **2018**, *69*, 463.
[180] IEA, *IEA, International Energy Agency* **2019**.
[181] H. Becker, J. Murawski, D. V. Shinde, I. E. L. Stephens, G. Hinds, G. Smith, *Sustain. Energy Fuels* **2023**, *7*, 1565.
[182] H. Idriss, *Energy Technol.* **2021**, *9*, 2000843.
[183] IRENA, Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal. IRENA, International Renewable Energy Agency; **2020** [cited 2024 Jun 27], https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction.
[184] X. Zou, Y. Zhang, *Chem. Soc. Rev.* **2015**, *44*, 5148.
[185] A. Valente, D. Iribarren, J. Dufour, *Int. J. Hydrogen Energy* **2019**, *44*, 20965.
[186] P. L. Cruz, J. Dufour, D. Iribarren, *Renew. Energy* **2023**, *210*, 424.
[187] A. A. Ismail, D. W. Bahnemann, *Sol. Energy Mater. Sol. Cells* **2014**, *128*, 85.
[188] J. Qi, W. Zhang, R. Cao, *ChemElectroChem* **2019**, *6*, 2762.
[189] F. Safari, I. Dincer, *Energy Convers. Manage.* **2020**, *205*, 112182.
[190] A. Valente, D. Iribarren, J. Dufour, *Sci. Total Environ.* **2021**, *756*, 144132.

Antonella Sola is a researcher at the University of Modena and Reggio Emilia (Italy). After completing her Ph.D. in Materials Engineering with a dissertation dedicated to functionally graded materials, she has been working on composites, advanced coatings and biomaterials. In her past position as the Science Leader in Active Materials at the Commonwealth Scientific and Industrial Research Organization, CSIRO (Australia), she focused her research on additive manufacturing and processing technologies for the development of innovative materials and systems with improved functionalities. She is now taking on a new role in life cycle assessment and environmental sustainability. She has published more than 100 papers, coauthored a monography about the fused filament fabrication of composite materials, and presented at numerous international conferences.

Roberto Rosa is Associate Professor of Chemical Foundations of Technologies at the Department of Sciences and Methods for Engineering of the University of Modena and Reggio Emilia (Italy). His research is focused on the development and application of the Life Cycle Assessment (LCA) methodology, for the reliable quantification of the potential environmental impacts associated with products and services, with a special interest for green and sustainable chemical practices. He is the author of more than 100 scientific publications indexed in the most renowned databases.

Anna Maria Ferrari is currently Full Professor of Chemistry at the Department of Science and Methods for Engineering of the University of Modena and Reggio Emilia (Italy). She graduated in Chemistry from the University of Modena and Reggio Emilia in 1993 and received her Ph.D. in Chemical Science in 1997 from the Universities of Parma, Modena and Ferrara (Italy). She holds courses in Chemistry and in Product and Process Sustainability for the bachelor and master degrees in Management Engineering and Mechatronics Engineering in Reggio Emilia. Coordinator of several European and national projects, she is author of more than 130 publications in international journals and more than 200 contributions in national and international congresses. Her research activity is mainly focused on the design management of sustainable processes and products. Since 2005, she has been coordinating the LCA Working Group, a research group devoted to the development and application of LCA (Life Cycle Assessment) methodology as a tool for assessing the potential environmental impacts associated with products, processes, and services in order to support decision making. Her research spans across a variety of industrial sectors such as construction materials, waste management, agricultural systems and nanotechnologies, and is delivered in collaboration with leading companies and institutions in the field of environmental sustainability. Lately, her scientific work has been addressed to the development of a holistic approach that takes into account not only environmental, but also economic and social issues, through the integrated LCM (Life Cycle Management) model, i.e., LCA-LCC-SLC (Life Cycle Assessment-Life Cycle Costing-Social Life Cycle Assessment).