

Systematic Review

Hydrogen Production via Water Electrolysis: A Bibliometric and Systematic Review of LCA Methodologies and Electricity Supply Impacts

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Abstract

Hydrogen production via water electrolysis (WE) has emerged as one of the key pathways for decarbonizing hydrogen supply, leading to a rapid increase in Life Cycle Assessment (LCA) studies evaluating its environmental performance. The primary objective of this work is to characterize the evolution of the scientific literature and examine the methodological approaches adopted in these LCA studies addressing hydrogen production via water electrolysis. Accordingly, this article combines a bibliometric analysis of 386 publications retrieved from Scopus and Web of Science with a PRISMA-based systematic review of selected studies. It revealed a considerable increase in articles published on the topic in the last 10 years, with major contributions coming mainly from China, Germany, and North America. Keyword co-occurrence analysis indicated that WE has developed into a well-established research topic in the LCA literature and highlighted “life cycle assessment”, “hydrogen production”, and “water electrolysis” as the main searched keywords. Additionally, a systematic assessment of 23 selected articles indicated that most publications adopted a functional unit of 1 kg H₂ and system boundaries of cradle-to-gate, with cradle-to-grave also being frequent. ReCiPe 2016 emerged as the most widely adopted life cycle impact assessment (LCIA) methodology, while climate-related indicators such as Global Warming Potential (GWP), greenhouse gas emissions (GHG), and carbon intensity (CI) were the most applied impacts, being addressed by all reviewed studies. The main contributor for these global emissions was the different types of electricity supplies, showing that electricity grids composed mainly of fossil fuels contributed largely to the increase in emissions, while renewable energy, in particular wind and solar power, were often associated with substantially lower emissions.

Keywords: life cycle assessment; water electrolysis; hydrogen production; renewable energies; sustainability



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1. Introduction

Over the past couple of decades, hydrogen has increasingly been recognized as one of the most promising options in the transition towards low-carbon energy systems, attracting growing interest within the scientific community, industrial planning, and climate governance frameworks. This growing interest is also supported by regulatory and policy frameworks that promote zero-emission transport and low-carbon energy carriers. The European Union is encouraging the development of zero-emission transport through

the implementation of CO₂ emission standards, the Renewable Energy Directive (RED), and the European Green Deal policies. To this end, measures include developing supporting infrastructure, electrifying freight transport, establishing priority zero-emission transport corridors, and improving fleet management. These policy instruments contribute to creating favorable conditions for the deployment of renewable electricity, hydrogen technologies, and related infrastructure, reinforcing the relevance of assessing the environmental performance of hydrogen production pathways [1]. With a calorific value of approximately 140 MJ/kg, hydrogen presents a significantly higher energy content per unit mass compared to conventional hydrocarbon fuels, such as gasoline (44 MJ/kg) and diesel (45 MJ/kg) [2,3].

Among the available hydrogen production pathways, water electrolysis (WE) has gained increasing relevance as a key technology for the sustainable production of hydrogen. Unlike conventional thermochemical pathways such as Steam Methane Reforming (SMR), WE does not rely on carbon-containing feedstocks since water is decomposed into hydrogen and oxygen using electrical energy, making it a structurally attractive option in the context of long-term decarbonization strategies [4]. This electrochemical process is also characterized by its ability to produce high-purity hydrogen, and its technologies exhibit high operational flexibility, allowing them to be implemented from small-scale production units to large-scale industrial installations [5]. Over time, multiple WE technologies have been developed and refined, each characterized by different materials, efficiency levels, ways of operating, and degrees of technological maturity. The 3 main WE technologies that have been the most frequently reported in the literature to date are alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEMWE), and solid oxide electrolysis cells (SOEC) [6]. Other more recent technologies, such as Anion Exchange Membrane (AEMWE), have also shown potential in affirming itself in the field; however, these are still primarily in the laboratory/research stage and, therefore, were not included in this bibliographic and systematic evaluation [7]. Out of the considered technologies, AWE is the most mature and widely developed, employing a liquid alkaline electrolyte to transport hydroxyl ions between the electrodes, which are separated by a porous diaphragm to prevent gas mixing [3,6]. PEMWE uses a solid polymer electrolyte membrane that conducts the protons from the anode to the cathode, where hydrogen is produced following the water oxidation that happens at the anode [8,9]. SOEC operates at very high temperatures, at 500–850 °C, according to Arsad et al. [10] or even as high as 900–1000 °C, according to El-Shafie [4] and uses a solid ceramic electrolyte that conducts oxide ions, with water supplied as steam and reduced to hydrogen in the cathode. Recent developments in advanced WE technologies have significantly improved hydrogen production efficiency while reducing operational costs, making green hydrogen increasingly competitive as a sustainable energy carrier [11–15].

Despite the technological differences between the main WE pathways, their environmental performance is strongly shaped by external factors. Consequently, identical technologies may display substantially different environmental profiles depending on the conditions under which they operate. This complexity highlights the need for a comprehensive environmental assessment capable of a transparent comparison of different studies and scenarios. In this context, Life Cycle Assessment (LCA) allows a harmonized analysis of essential methodological elements, such as functional units (FUs), system boundaries, and impact categories related to different stages of the life cycle. It is a methodology responsible for evaluating environmental impacts of a product or a system through its entire service lifetime, analyzing all stages, including typically raw material acquisition, manufacturing, operation, and end-of-life disposal or recycling [6]. The LCA framework, defined by the ISO standards [16], is structured into four main phases, composed of goal and scope defini-

tion, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the results obtained. The outcomes of LCA studies are commonly reported using established impact assessment methodologies such as ReCiPe, Environmental Footprint (EF), and TRACI.

Within this framework, one of the most critical parameters that influence the environmental assessment of WE systems is the supply of electricity used to power the production of hydrogen. Various LCA studies indicate that electricity supply often outweighs the impacts associated with the manufacturing of the electrolyzers and the construction of the infrastructure. As a result, this factor becomes one of the most important parameters to be addressed in LCA studies of this topic, with a main focus on categories related to climate change and emissions [17].

Although several review articles have addressed hydrogen production technologies and the environmental assessment of electrolysis systems, comparatively few studies have combined bibliometric techniques with a PRISMA-based methodological review specifically focused on the evolution and methodological characteristics of LCA studies related to hydrogen production via water electrolysis.

This article presents a combined bibliometric and systematic review of LCA studies addressing hydrogen production via WE processes. The bibliometric analysis examines the temporal evolution over the years and the geographical distribution of the scientific publications in this area. A keywords co-occurrence map was also conducted to identify dominant research themes and emerging trends within the literature. The systematic review focuses on the methodological characteristics of the selected LCA studies through a PRISMA evaluation, including functional units, system boundaries, impact categories, and LCIA methods. Additionally, an electricity supply analysis is conducted to evaluate how different power generation mixes, renewable and non-renewable, affect the reported emissions and environmental impact results to produce hydrogen via WE in the literature.

It should be noted that the objective of this review is not to provide a comprehensive technological assessment of water electrolysis systems or recent developments in electrolyzer design and materials. Instead, the focus is placed on the evolution of the scientific literature and on the methodological characteristics adopted in LCA studies, providing a structured overview of how environmental assessments of hydrogen production via WE have been conducted.

2. Methodology

2.1. Database Search

For this study, a two-stage methodological framework was adopted, containing a global bibliometric analysis and a PRISMA-based systematic review focused on LCA studies of hydrogen production via WE (Figure 1).

The PRISMA-based screening procedure was structured into identification, screening, eligibility assessment, and final inclusion. During the screening stages, articles were evaluated according to certain inclusion and exclusion criteria. Studies that were chosen to be included focused on hydrogen production pathways and applied LCA indicators. Studies were excluded when they focused mainly on other factors, such as hydrogen storage, fuel cells, end-use applications, non-electrolysis production pathways, or techno-economic analyses without an environmental assessment component. The quality assessment of the included studies in the review was based on the clarity and completeness of methodological information reported. Particular attention was given to the article's environmental report and the LCA component. Studies that did not provide sufficient methodological detail to

support some sort of comparison across the reviewed literature were excluded from the final systematic review [18].

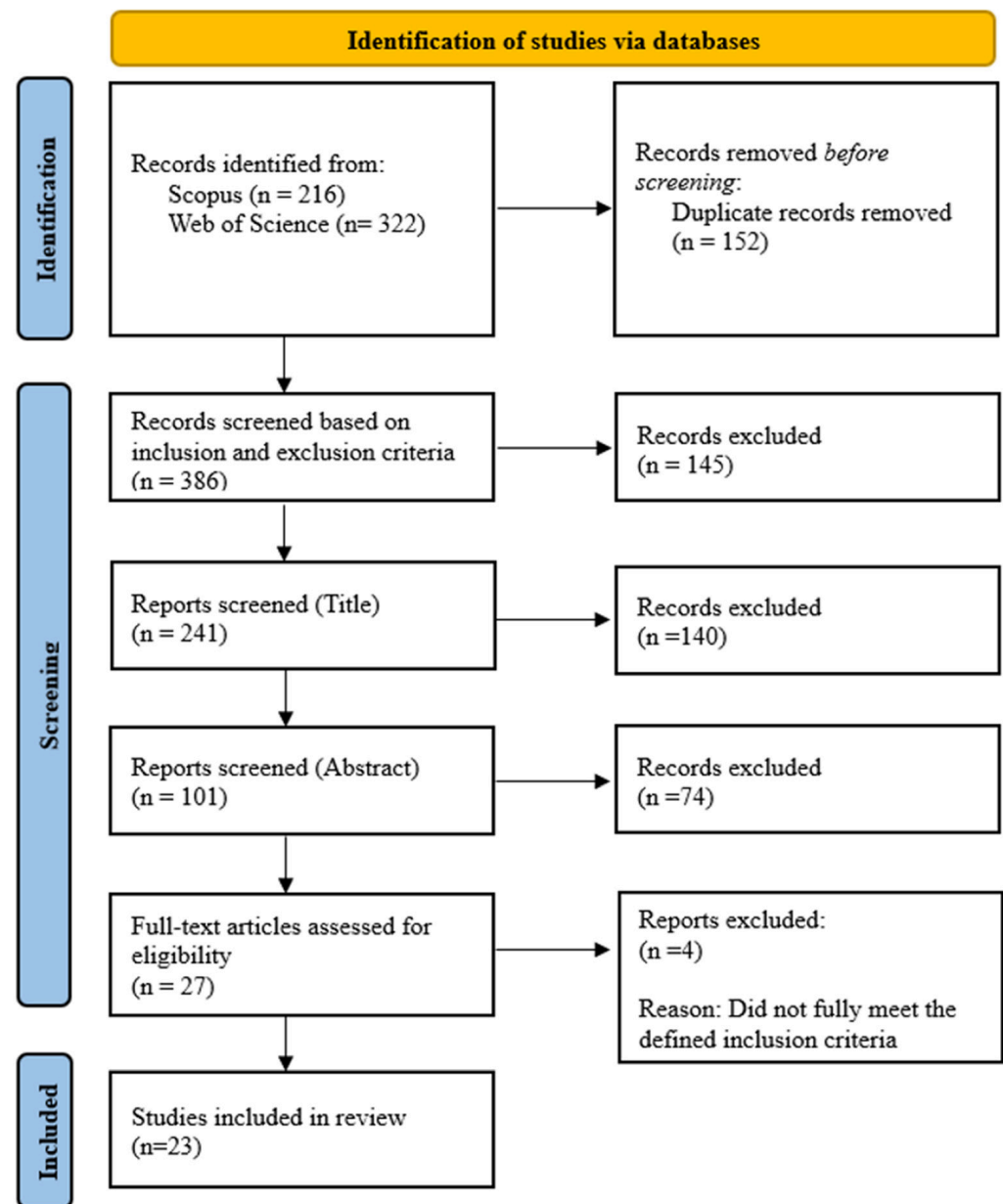


Figure 1. PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and final selection of studies included in the bibliometric and systematic review.

Two major bibliographic databases were chosen for this research, Scopus and the Web of Science Core Collection (WOS), due to their comprehensive coverage of scientific literature on the topic of this research. The initial search strategy was intentionally broad to ensure maximal coverage of articles that could be proven relevant to the topic. The following code search string was applied identically to both databases: (“hydrogen production”) AND (“life cycle assessment” OR “LCA”) AND (“water electrolysis OR “alkaline electrolysis” OR “AWE” OR “PEM electrolysis” OR “PEMWE” OR “solid oxide electrolysis” OR “SOEC” OR “high temperature electrolysis” OR “HTE”)”). In the context of this review, the term “high-temperature electrolysis (HTE) pathways” is consistently classified under solid oxide electrolysis cell (SOEC) technology, as HTSE is exclusively implemented using SOEC systems in the existing literature.

The research included all the main hydrogen production technologies associated with WE, as well as the LCA component. This initial search generated 216 records from Scopus and 322 from WOS. All the records were then exported into Zotero 9, in which duplicated articles originating from the overlap of the two databases were removed using manual and automated verification. This contributed to a dataset containing 386 unique documents.

Following the initial broad retrieval phase, a second filtering stage was applied to refine the dataset for the systematic review. This filtering stage focused on removing data that did not focus completely on LCA of hydrogen production, such as works focused primarily on other hydrogen applications like storage or fuel cells, and other technologies outside of WE technologies. After this filtering stage, 145 articles were removed, and 241 went through to the next phase.

Next, a screening process was conducted by reading the titles of all articles that passed the filtering phase, with the aim of evaluating their relevance to the focus of the review. Based on this analysis, 101 articles were selected for abstract evaluation. In the abstract evaluation, 27 articles went through to the next phase, which consisted of reading the articles.

Finally, after a detailed analysis of the full texts, 4 more articles were excluded for not fully meeting the defined inclusion criteria, resulting in a final set of 23 studies included in the systematic review (see full list in Table S1, in the Supplementary Material).

2.2. Bibliometric Analysis

The bibliometric analysis was conducted after the database search, compiling the data extracted from Scopus and WOS and removing duplicate articles with Zotero. The data was then converted into a CSV format for screening analysis and an RIS format for VOSviewer version 1.6.21, which was used to conduct bibliometric networks and visualizations of keyword co-occurrence. QGIS was employed to produce a geographical map highlighting the countries with the highest scientific output in the analyzed literature. Lastly, keyword co-occurrence maps were used to analyze relationships between research topics, allowing a clearer interpretation of the thematic structure and the actual content of the analyzed studies. The analysis was limited to the 200 highest-occurrence keywords, and a thesaurus file was applied in VOSviewer to harmonize similar keywords such as “life cycle” and “life cycle assessment” or “water electrolysis” and “electrolysis” to focus mainly on the overall research topics and not solely on words, which can lose relevancy when they are fragmented by synonyms.

2.3. Systematic Analysis

This review’s systematic analysis focused on identifying and exploring the methodologies used in LCA articles on the production of hydrogen through WE. In particular, the analysis investigated how the reviewed studies defined and applied key methodological elements, such as functional unit, system boundaries, LCIA, and impact categories. In addition, the characterization of electricity supplied used for different WE technologies and their associated emission profiles was considered. This approach enabled a structured assessment of methodological consistency across studies while supporting a comparative interpretation of emissions associated with different electricity supply configurations.

The objective was not to harmonize or normalize the environmental results reported by different studies, but rather to identify the methodological approaches adopted throughout the literature and discuss how differences in methodological assumptions may influence the interpretation and comparability of the reported outcomes.

3. Bibliometric Analysis of LCA Studies on Water Electrolysis

3.1. Publication Trends and Temporal Evolution

An overview of the temporal evolution of scientific publications on LCA of hydrogen production via WE between 2006 and 2025 is shown in Figure 2. This temporal evolution revealed limited research activity between 2006 and 2016, with annual publications generally reporting below 5 studies per year, corresponding to an average of approximately 3.5 publications per year during this period. This lower initial phase reflects a low publication output, which can be attributed to the limited role of WE in early green hydrogen production research studies, which were predominantly focused on fossil-based production pathways.

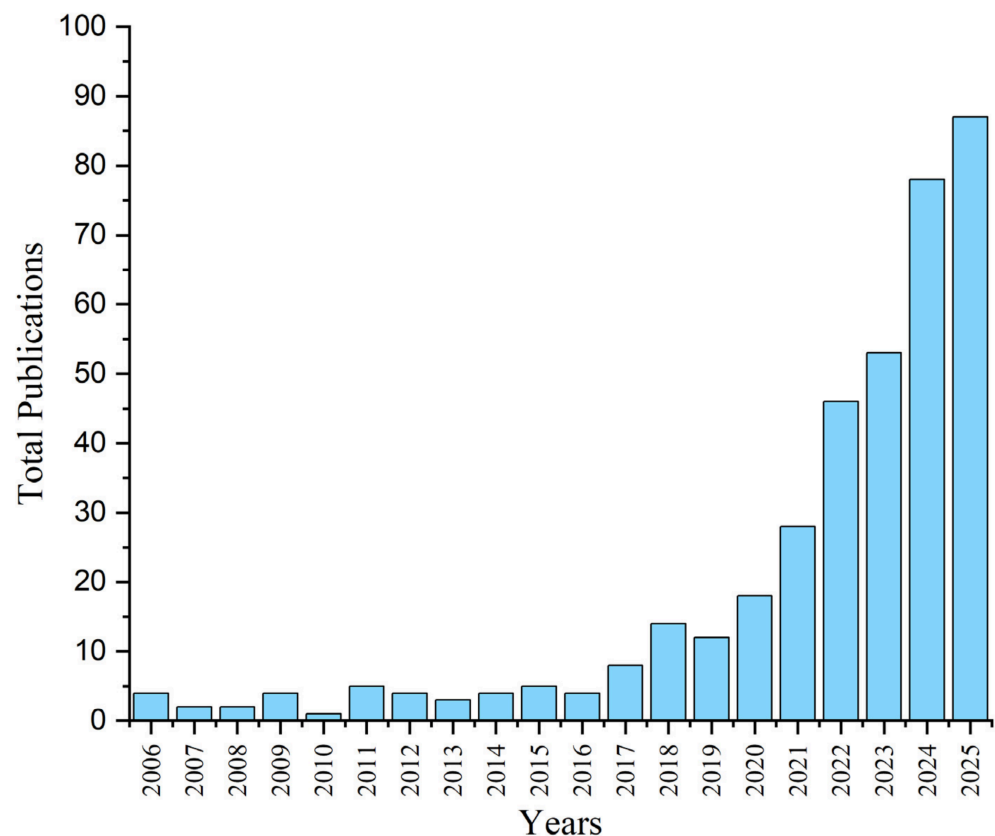


Figure 2. Temporal evolution of scientific publications on LCA of hydrogen production via WE between 2006 and 2025.

From 2017 onwards, Figure 2 shows a clear and significant increase in publication activity, indicating a shift from a low-researched topic to a more consistent and growing body of literature. This growth becomes even more pronounced after 2020, with the number of publications increasing by almost 50% from 2021 to 2022, followed by another major increase between 2023 and 2024. The highest publication output was observed in 2025, which recorded a peak of 87 publications, highlighting the consolidation and maturity of this research field. This expansion can be attributed to the growing focus on replacing fossil-fuel-based energy systems, completing decarbonization objectives, and supporting transitions towards low-carbon energy pathways [19,20].

This recent acceleration can be scientifically associated with the growing strategic importance of green hydrogen in global decarbonization pathways. Green hydrogen is increasingly recognized as a key energy vector for achieving Net Zero Emissions targets by 2050, particularly because it can support the integration of renewable electricity while contributing to the decarbonization of industrial and transport sectors. At the same time,

water electrolysis has gained attention as one of the most promising routes for sustainable hydrogen production when powered by renewable energy. This has stimulated both scientific and industrial interest in improving electrolyzer efficiency, durability, cost, materials, and system performance. As a result, the rapid increase in publications in recent years can be linked not only to technological advances in alkaline, PEM, SOEC, and AEM electrolysis, but also to the expansion of policy frameworks, investment programs, and national hydrogen strategies aimed at scaling up green hydrogen production and infrastructure [21].

3.2. Leading Countries and Locations in Terms of Publication Numbers

Figure 3 represents a worldwide distribution of scientific publications on LCA related to hydrogen production through WE, based on the 386 articles selected for bibliographic review. This distribution reveals a strong concentration of publications in certain regions of the world. China emerges as the leading country on this topic with the highest number of publications, 58. This higher number may represent a growth in the scientific field of renewable energies and hydrogen production, driven by newly developed national hydrogen strategies, increasing policy support, and a clear shift towards green hydrogen technologies that are expected to dominate future hydrogen supply [22]. The geographical distribution of publications appears to follow current global investment trends in hydrogen technologies, where China has strong governmental support and large-scale deployment of electrolysis projects, while European research activity remains substantial but is distributed across multiple Member States rather than concentrated within a single country.

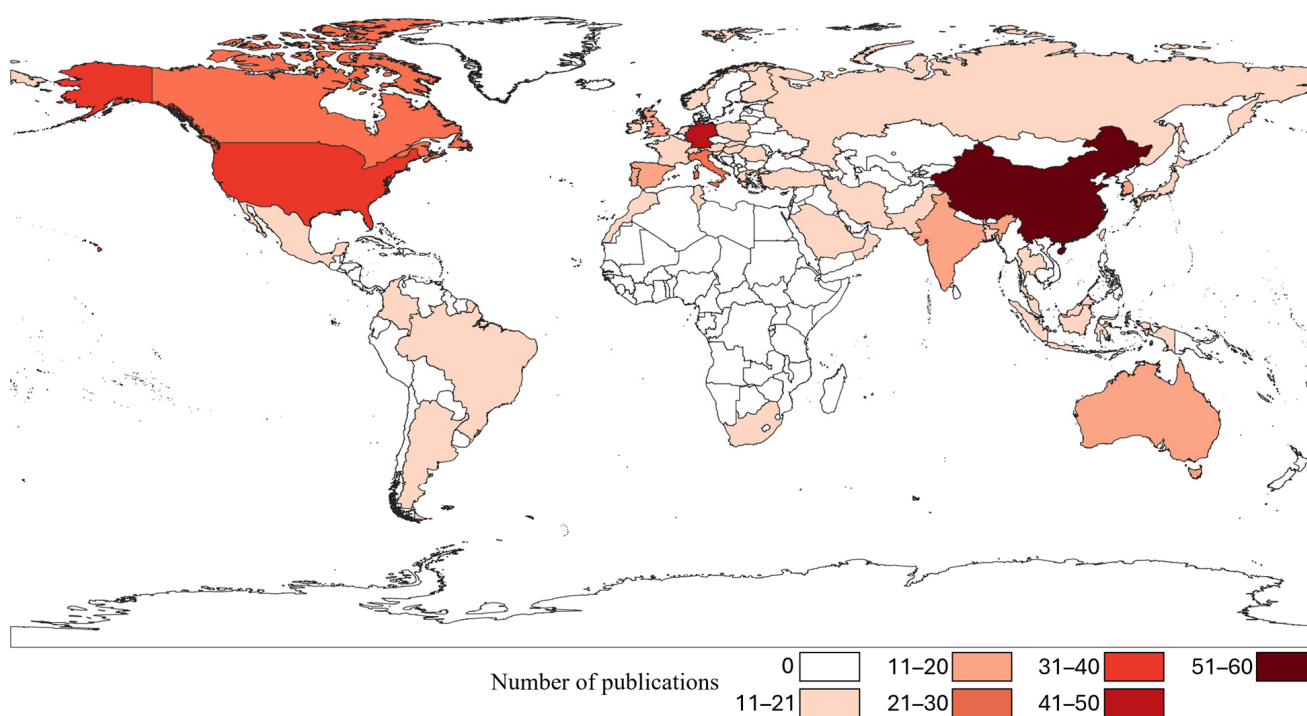


Figure 3. Worldwide distribution of scientific publications on LCA related to hydrogen production via WE, based on the number of publications per country and locations. The figure is intended solely to illustrate the geographical distribution of scientific publications and does not represent any political position or viewpoint of the authors regarding territorial claims, disputed boundaries, or sovereignty.

Aside from China, Asia features other countries and locations with strong contributions, namely India with 19 publications and South Korea with 18. From the European continent, Germany appears as the largest researcher on the topic with 47 publications, followed by Italy with 22 publications and Spain with 17 publications. North America also

appears with a large percentage of published articles, with 33 scientific publications from the United States and 28 from Canada. Finally, Australia also presents a significant output with 17 published articles.

3.3. Keywords Co-Occurrence and Thematic Evolution

For this study, defining the most relevant keywords was a crucial step to explore the thematic structure of the literature and to identify the main research topics associated with LCA applied to hydrogen production. These types of maps highlight the relationship between research fields by directly analyzing the content of the article's main focuses, revealing the dominant themes, emerging topics, and connections between studies, as explained by Donthu et al. [23]. Figure 4 presents the keyword co-occurrence network map generated using VOSviewer, based on Scopus and WOS. The keyword co-occurrence distribution of LCA-based WE hydrogen production studies is presented in Figure 5.

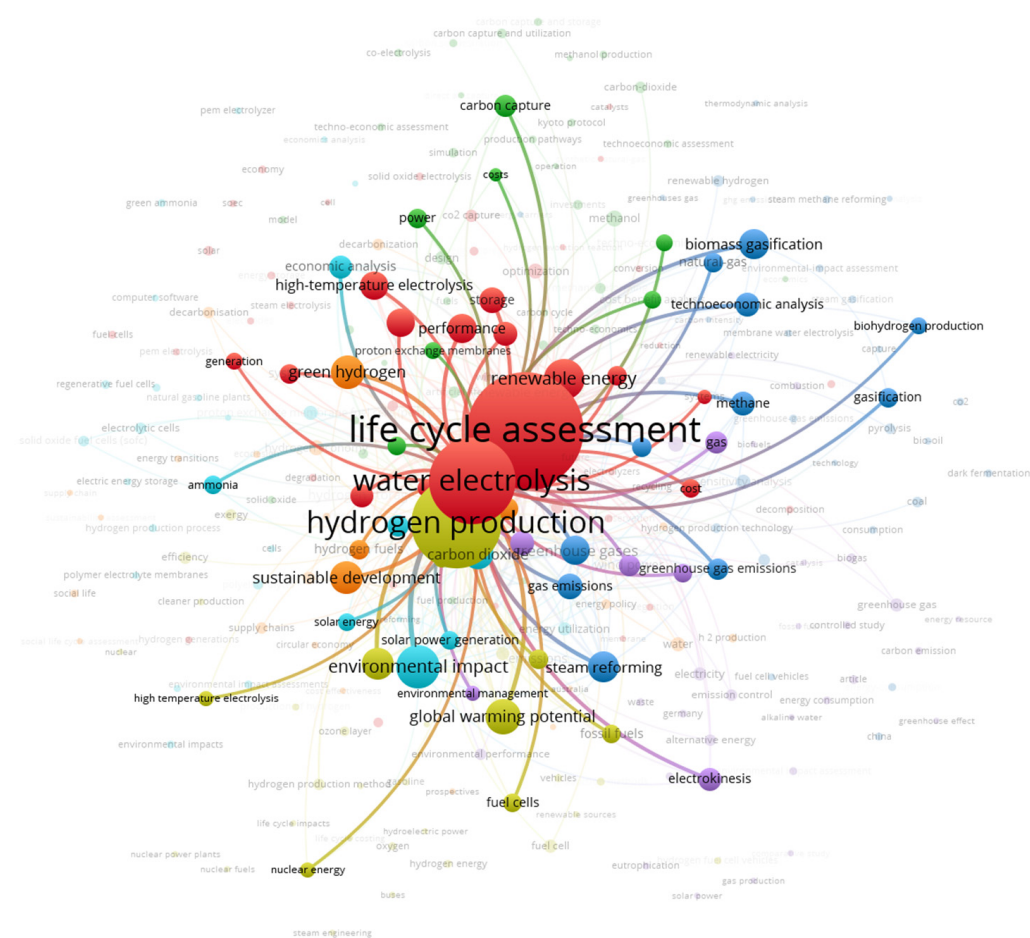


Figure 4. Keyword co-occurrence network map generated using VOSviewer, based on Scopus and WOS.

Within the bibliometric research, “life cycle assessment” was the most dominant searched keyword, emerging as a central keyword in the analysis of the literature with over 400 occurrences. Within this context, “water electrolysis” and “hydrogen production” also appear as highly central and strongly interconnected keyword topics, indicating that WE is predominantly treated as the main production route in these types of LCA-based studies, rather than as a comparative option. This factor could demonstrate the growth of WE as an emerging technology compared to other green and fossil energy technologies. In contrast, a lower centrality of “water electrolysis” would generally reflect a more limited

role, possibly indicating that WE is not yet a viable technology and is used only as a secondary comparison in other studies related to hydrogen production.

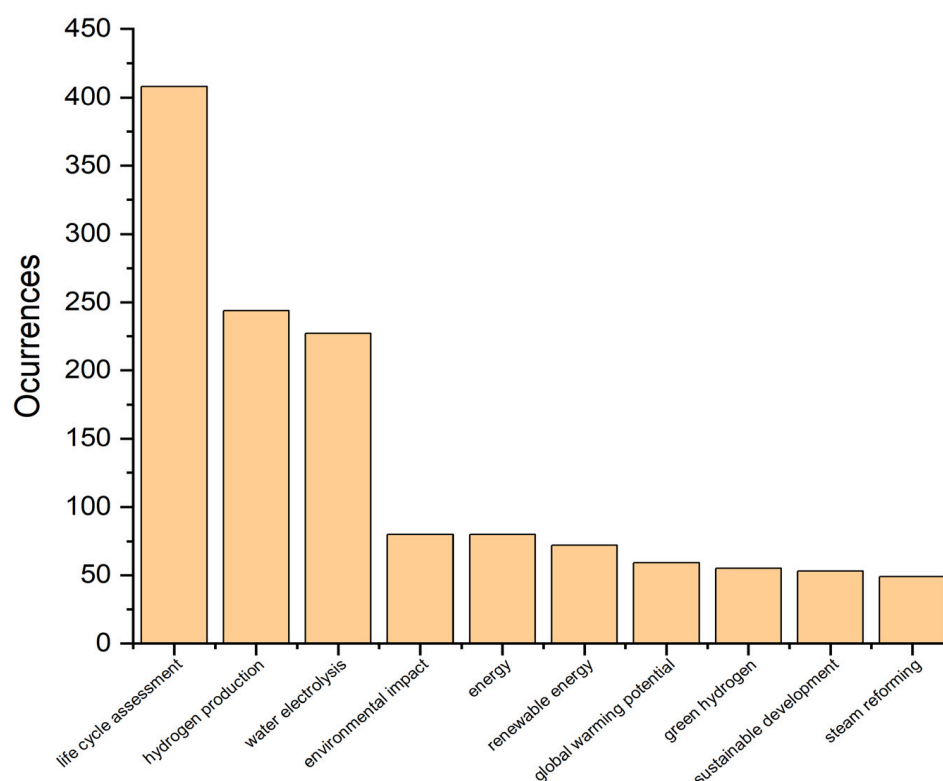


Figure 5. Keyword co-occurrence distribution of LCA-based WE hydrogen production studies.

In addition to the dominant electrolysis-related cluster, smaller but defined clusters associated with “steam reforming”, “methane”, and “carbon capture” are also observed. Their presence suggests that fossil-based pathways are frequently included as benchmark or reference scenarios in LCA studies, enabling comparative assessments against low-carbon alternatives such as WE. Similarly, alternative renewable-based routes, including “biomass gasification”, “gasification”, and other biohydrogen-related technologies, appear as distinct clusters, indicating their role as comparative pathways within the analyzed literature [10].

Keywords such as “energy” and “green hydrogen” also appear as some of the most occurring keywords, revealing that these LCA studies not only limit themselves to the environmental aspects of the studies, but also the energetic considerations, including different types of energy supplies that could be used to power the systems used.

“Global Warming Potential”, “gas emissions” and “greenhouse gas emissions” also emerge as one of the most prominent keywords, affirming their role as the primary impact category used to assess and compare hydrogen production pathways. Its frequent occurrence confirms that greenhouse gas emissions are the most dominant metric for evaluating.

4. Systematic Review of LCA Studies on Water Electrolysis

4.1. Functional Units

In LCA, the FU provides a reference basis for quantifying inputs and outputs, enabling consistent comparison between processes and systems. In the context of WE-based hydrogen production, the definition of the FU plays a crucial role in ensuring transparency and comparability across studies, particularly given the strong dependence of results on energy supply and system configuration [24–26].

In the reviewed WE LCA studies, a clear predominance of a selected functional unit is observed, with most studies defining the FU as 1 kg of hydrogen produced (Table 1). This FU usage has been considered intuitive and suitable for reporting impact categories and has been widely adopted in more recent years, especially studies published after 2014, indicating a progressive convergence towards harmonized reporting practices [26]. Out of the 23 studies, 20 adopted 1 kg H₂ as the main FU of their LCA assessments (Table 1).

Table 1. Functional units adopted in WE LCA studies included in the systematic review.

Functional Unit (FU)	Typical Application	Number of Studies
1 kg H ₂	Standard LCA reporting and certification	20
1 MJ H ₂	Energy efficiency focused studies	1
1000 kg H ₂ h ^{−1}	Industrial-scale and techno-economic analysis	1
50 t H ₂ day ^{−1}	Industrial-scale and techno-economic analysis	1

However, a small number of studies still employ alternative choices related to their FU definition. In a study conducted in relation to HTE, Patyk et al. [27] define the FU as 1 MJ of hydrogen, more consistent with the article's focus on energy efficiency, rather than the hydrogen supply benchmarking used in more traditional LCA studies. This choice reflects earlier LCA practices, when alternative functional units were more commonly adopted, particularly in studies published prior to the widespread standardization around 1 kg of hydrogen produced.

More recently, Barbera et al. [28] adopted a capacity-based FU of 1000 kg H₂ per hour, reflecting a more industrial approach in which environmental impacts are linked to plant-scale production, rather than normal hydrogen outputs. This approach is suited to process design and techno-economic analysis but is more limited when applied to the comparison of LCA studies.

Kadam et al. [29] utilized a FU based on an industrial scale of 50 metric tons of hydrogen per day (TPD), focusing as well on a more industrially oriented study. This publication also notes that most existing LCA publications focus on small-scale facilities or individual technologies, which can limit the understanding of how these systems perform at a bigger scale. By selecting this FU, it was possible to account for the efficiencies of larger facilities and to reflect how fixed costs are spread across a greater number of produced units, providing a more realistic economic evaluation of the industry.

4.2. System Boundaries

Defining system boundaries is a vital methodological step in LCA studies, since it establishes which processes and life cycle stages will be included in the environmental evaluation, thereby determining the resulting impact value estimations. In these types of studies, system boundaries can vary considerably depending on the scope and final objective of the study. Differences can occur if hydrogen is treated as a final energy carrier or as an intermediate product within a broader energy or transport system. In WE LCA cases, defining whether hydrogen is considered a final product or an intermediate carrier will determine the inclusion or exclusion of different upstream (such as material extraction and plant construction) and downstream processes (such as storage, distribution, or end-use) [30].

Of the 23 articles reviewed in the final process of screening, the cradle-to-gate system boundary showed a clear prominence, reflecting the prevailing focus on hydrogen

production and the stages of its extraction and plant-related impacts (Table 2). Specifically, 13 studies adopted a cradle-to-gate (C-T-G) approach, which generally included raw material extraction, manufacturing of electrolyzer components and auxiliary systems, infrastructure construction, hydrogen production and, in some cases, some other operations. Within these boundaries, some variations were observed in the definition of the system. While many studies have limited the system boundary to hydrogen production in the electrolyzer, other articles have included processes that could be considered at other types of system boundaries. Koj et al. [31] and Zhang et al. [32] included hydrogen storage and compression. Other studies have also included hydrogen compression and purification [27]. Although these studies fall within a cradle-to-gate framework, they demonstrate a certain methodological difference and heterogeneity. This boundary choice is closely linked to the predominant use of midpoint impact categories, as cradle-to-gate assessments tend to focus on direct environmental impacts associated with individual processes and production stages. As a result, these studies put less emphasis on damage-oriented indicators that account for broader effects on human health, ecosystems, or resource depletion.

Table 2. System boundary definitions adopted in the reviewed LCA studies.

System Boundary	Main Typical Included Stages	Number of Studies
Cradle-to-Gate	Raw material extraction; electrolyzers and auxiliary systems manufacturing; infrastructure construction; hydrogen production and compression in some cases	13
Cradle-to-Grave	Raw material extraction; electrolyzers and auxiliary systems manufacturing; infrastructure construction; hydrogen production; hydrogen compression and transport; decommissioning of infrastructure and disposal	7
Well-to-Pump	Raw material extraction; electrolyzers and auxiliary systems manufacturing; infrastructure construction; hydrogen production; hydrogen compression and transport; end-point delivery of fuelling stations	2
Well-to-Production	Raw material extraction; electrolyzers and auxiliary systems manufacturing; infrastructure construction; hydrogen production	1

Seven articles adopted a cradle-to-grave (C-T-GR) system, incorporating an analysis beyond hydrogen production and compression. This approach incorporates all stages of the cradle-to-gate system and considers additional endpoint configurations. For these articles, the main phase included in the analysis was the end-of-life treatment of the plants. This final stage may include the dismantling of all equipment, transport of waste materials, recycling, and disposal through landfill or incineration. Zaki et al. [33] adopted a cradle-to-grave boundary, modeling the decommissioning and dismantling of electrolyzer stacks and other plant components, followed by the transport and treatment of waste materials through recycling, landfilling, or incineration. Ghandehariun and Kumar [34] followed a similar approach, modeling the dismantling of every unit of operation within the hydrogen supply chain, including the alkaline electrolyzer, wind turbines, compressors,

and hydrogen pipelines, and the recycling of metals and other waste components. The authors also report that material recovery at the end of the life cycle stage can decrease the total emissions, in particular due to the metal recycling provided from the wind turbines and infrastructure that can avoid the production of aluminum, iron, copper, and steel for other applications.

A smaller group of studies used a well-to-pump (W-T-P) approach, with two articles reviewed. In these studies, the hydrogen produced was not evaluated as an independent final output but rather as a step that goes through phases of compression, storage, transport, and delivery to refueling stations, offering a more complete view of the hydrogen supply chain. A representative example of a “pump” system is described by Kim and Kim [35], in which the system boundary is subdivided into seven sequential phases (J1–J7), representing the complete hydrogen chain. These phases include (J1) hydrogen production via WE (J2), hydrogen compression (J3), pipeline transport (J4), liquefaction and storage (J5), transport of liquefied hydrogen (J6), and delivery at hydrogen refueling stations (J7). In this article, the “pump” represents the hydrogen delivered to the refueling station, while hydrogen utilization and end-of-life are excluded. The publication also incorporates a well-to-gate approach (J1–J2) to align its study with others on the same frontier. In turn, Siddiqui and Dincer [36] also opted for a comparative well-to-pump approach with several different routes, namely WE, SMR, coal gasification, biomass gasification, methanol hydrogen, and ethanol hydrogen.

Lastly, Al-Ghussain et al. [37] adopted a well-to-production (W-T-PR) system boundary, covering the life cycle of renewable electricity supply and hydrogen generation. This approach is functionally similar to the cradle-to-gate boundary, incorporating the material extraction, manufacturing of the plant components, and hydrogen production, excluding compression, storage, transportation, and plant decommissioning.

4.3. Impact Categories

The selection and the definition of impact categories represent an extremely important methodological step in LCA studies, as they directly influence the interpretation of environmental results and determine the degree of comparability across different studies and scenarios. Since hydrogen is not naturally available in pure form and requires a substantial amount of energy for its production, multiple factors must be considered in order to conduct a comprehensive analysis and properly evaluate the environmental sustainability of hydrogen systems [38]. One way to evaluate these impacts is through the application of specific LCIA, such as ReCiPe, CML, or ILCD, that can provide a defined systematic procedure for the quantification and classification of environmental impacts.

The ReCiPe framework emerged as the most prominent adopted LCIA methodology among the reviewed studies, with six articles choosing this approach to evaluate their impact categories, presenting midpoint or endpoint indicators. ReCiPe 2016 Midpoint is used in multiple studies [34,39–41]. Earlier midpoint implementations can also be observed in Bareiß et al. [8] and Patyk et al. [27] using the ReCiPe 2008 version. These indicators focus on quantifying environmental impacts at an intermediate level, focusing on short-term direct impacts on the environment such as Global Warming Potential (GWP), Terrestrial acidification, and Freshwater and Marine eutrophication [42]. In contrast, Dincer and Agelin-Chaab [43] decided to apply endpoint indicators to evaluate impacts into damage-oriented indicators related to human health, ecosystems, and resource availability. CML methodology was adopted by four articles [30,33,37,44]. This methodology is a problem-oriented approach, focusing on midpoint indicators for more direct impacts to the environment. Some of the main impact categories used by these CML studies include

GWP, Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), and others.

TRACI 2.1 methodology is applied primarily for regions in North America because it provides characterization factors specifically tailored to those regions [33]. This methodology was adopted by Hannouf et al. [45] a study conducted in the United States and Zaki et al. [33] in Alberta, Canada. Some of the main indicators used were Climate Change, Acidification, Eutrophication, and Ozone Depletion. Zaki et al. [33] adopts a combined LCIA approach, applying both ReCiPe and TRACI methodologies in the same study.

Environmental Footprint 3.0 (EF 3.0) was adopted by three studies, being a methodology recommended by the European Commission for assessments within the EU focusing on impact categories such as Total Climate Change (CC-T), Acidification (EQ-FTA), Freshwater Ecotoxicity (EQ-FE), and others [29,32,46].

At last, IPCC Specific Metrics were applied by three studies to compare different time horizons. Patel et al. [47] directly compared GWP20 and GWP100 to compare short-term impacts with long-term ones, while Valente et al. [48] utilized GWP100 for their prospective study for the years 2030 and 2050. Affandi et al. [49] also utilized GWP100 for a dynamic life cycle assessment (DLCA) framework, estimating the environmental impacts over a 25-year period.

In addition, a subset of the reviewed literature did not follow a determined LCIA framework, instead focusing solely on Greenhouse Gas (GHG) emissions as a stand-alone metric.

This systematic review enabled the identification of 16 impact categories used across the assessed LCA studies, as shown in Figure 6. It provides a comparative approach to the frequency with which impact categories were reported across the review studies. The distributions show clear prominence around certain indicators while other remaining categories appear with progressively lower frequency.

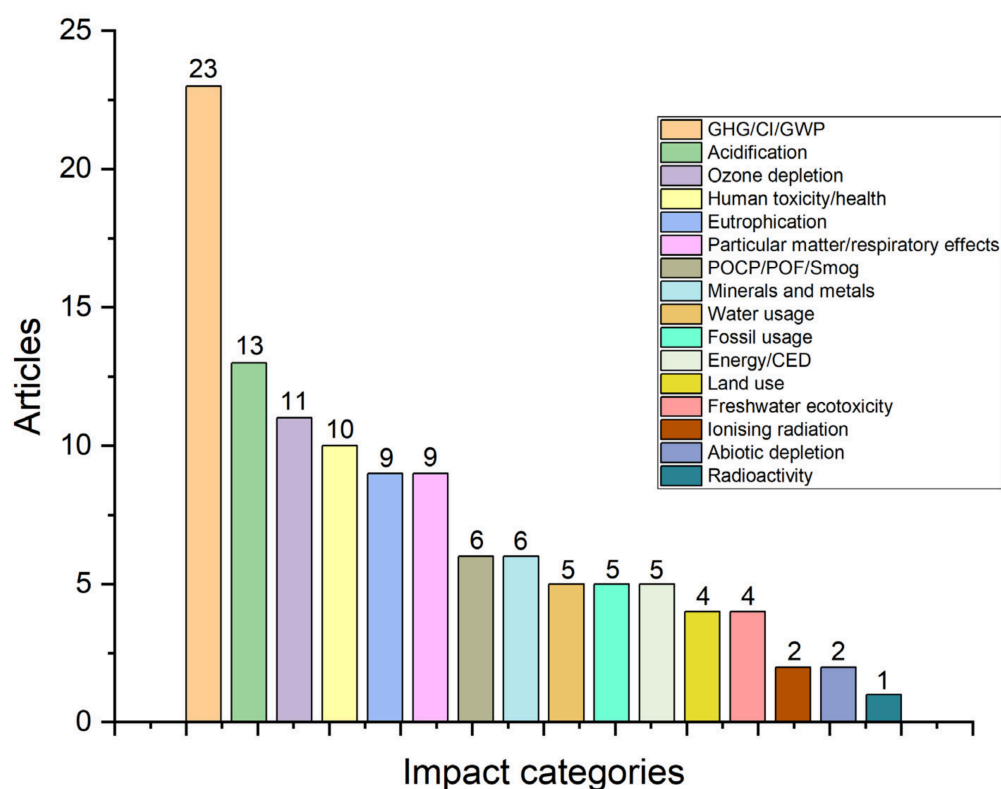


Figure 6. Frequency of environmental impact categories reported in the reviewed LCA studies on hydrogen production via WE.

From the analyzed literature, it was observed that emission-related impacts associated with global warming were the most prominent. Impact categories such as GHG, CI, and GWP were the most frequently reported, being used as indicators in all articles included in the systematic review. As previously mentioned, in several studies this category was even applied as the sole main indicator, as observed in Kim and Kim [35], Santana et al. [50], and Al-Ghussain [37]. The highest emissions value was reported by Lee et al. [41] for hydrogen production using AWE, powered by the current South Korean electricity mix, with 30.7 CO₂ eq per kg H₂. The lowest value was reported by Zhang et al. [32], using a combination of onshore wind power and PEM electrolysis with a value of 0.09 kg CO₂eq per kg H₂. This pattern indicates that most of the analyzed studies prioritize the quantification of GHG emissions and carbon-related indicators in comparison to other environmental indicators. Acidification emerged as the second most commonly used impact category (13 studies), followed by ozone depletion (11 articles) and human toxicity/health (10 studies). Eutrophication and particular matter/respiratory effects were both approached by nine different studies, and POCP/POF/SMOG and minerals and metals by six articles. Water usage, Fossil usage, Energy/CED, Land use, and Freshwater ecotoxicity were used by five articles or fewer, and ionizing radiation and Abiotic depletion were present in two articles. Lastly, Radioactivity was the least common category, only utilized by one article.

Overall, Figure 6 highlights an imbalance in the selection of the impact categories. While GHG emissions indicators were universally reported, other categories such as resource use, water consumption, ecotoxicity, ionizing radiation, abiotic depletion, and radioactivity were only included in a limited number of studies.

4.4. Electricity Supply

Electricity supply is a key driver of LCA global emissions produced via WE, as the operational electricity utilized by the electrolyzers represents the largest contribution to life-cycle emissions. Consequently, variations in carbon intensity can lead to substantial variations in reported values, particularly when comparing renewable and fossil-based electricity.

As shown in Table 3, this systematic review revealed that the LCA studies that relied on grid electricity as their main electricity source consistently reported higher emission values in comparison to systems that were fully powered by renewable energies. In addition to higher values, the results also presented a dispersion of emissions values across the analyzed grid electricity studies, indicating noticeable variability between the different studies using the same type of electricity. This variability can be largely attributed to differences in the carbon intensity of electricity supply, as national electricity grids will differ significantly in their composition and in the relative percentage of fossil fuels and renewable energies used [51,52]. Among the analyzed studies, the highest GHG emissions reported for hydrogen production via WE were 30.7 kg CO₂-eq/kg H₂ [41].

This higher impact is largely linked to the characteristics of the South Korean electricity grid considered in the article, which is dominated by fossil fuels, being composed of circa 40% coal, 22% natural gas, 30% nuclear energy, 4% wind energy, and 1% hydropower. This can also be observed in Hannouf et al. [45], Siddiqui and Dincer [36] Bareiß et al. [8], in which the electricity grids of Alberta in Canada, the United States, and Germany are characterized by having a high reliance on high-carbon electricity sources. The predominance of fossil fuel in its mix leads to higher indirect emissions that will be noted in the final global emission values of the LCA. Nevertheless, the variability reported across the reviewed studies should also be interpreted considering differences in methodological assumptions, including functional units, system boundaries, LCIA methods and model-

ing choices. Consequently, direct comparison of absolute environmental values between different publications should always be performed with caution.

Table 3. Summary of reported GHG emissions for WE based on different electricity sources, technology types and boundaries.

Electricity Supply	Technology Type	Emissions Range CO ₂ -eq/kg H ₂	Boundary	Article
Wind	AWE	1.68	C-T-G	[45]
	Onshore PEMWE	0.09		
	Onshore AWE	0.11		
	Onshore SOEC	0.21		
	Offshore PEMWE	0.9	C-T-G	[32]
	Offshore AWE	0.92		
	Offshore SOEC	1.49		
	AWE	0.68	C-T-GR	[34]
	AWE	1.03–2.18	C-T-GR	[33]
	AWE	0.43	C-T-G	[48]
	PEMWE (EU case)	1.82		
	PEMWE (India case)	2.04	C-T-G	[39]
	AWE	2.61–5.15		
	PEMWE	2.26–4.46	C-T-GR	[49]
	PEMWE	0.35–1.9	C-T-G	[37]
	PEMWE	0.6	C-T-G	[47]
	PEMWE	~0.6		
	AWE	~0.7	C-T-G	[53]
	AWE	0.74–2.86		
Solar	PEMWE	0.75–1.4	W-T-P	[35]
	SOEC	0.9–1.6		
	PV-PEMWE	9.37		
	PT-PEMWE	8.67	C-T-G	[44]
	AWE	2.57–5.09	C-T-GR	[33]
	PEMWE (EU case)	5.29		
	PEMWE (India case)	3.38	C-T-G	[39]
	PV-SOEC	1.03–1.87		
	CSP-SOEC	1.05–1.67	C-T-GR	[54]
	AWE	2.0–2.3		
	PEMWE	1.58–2.95	C-T-G	[37]
	PEMWE	2.5	C-T-G	[47]
	PEMWE	~2.3		
	AWE	~2.4	C-T-G	[53]
	CSP-SOEC	1.85	C-T-GR	[46]
Grid electricity	PV-AWE	1.52–3.11		
	PV-PEMWE	1.53–1.61	W-T-P	[35]
	PV-SOEC	1.61–1.92		
	Not Specified	28.6	W-T-P	[36]
	AWE	27.37	C-T-G	[45]
	PEMWE	29.5	C-T-G	[8]
	AWE	28	C-T-G	[48]
	AWE	4.27	C-T-G	[50]
	AWE	30.7	C-T-G	[41]

In contrast, the work by Santana et al. [50] illustrates the opposite effects when WE is supplied by a substantially cleaner electricity grid, exemplified by the Brazilian electricity mix. This publication reported the lowest values of emissions related to grid energy across the entire systematic review, presenting values of 4.27 kg CO₂-eq/kg H₂, which is nearly seven times lower than the 30.7 kg CO₂-eq reported for South Korea and the

rest of the fossil-dominated electricity grids of various countries. This Brazilian grid is characterized by a high share of renewable energy, consisting of 56.8% Hydropower, 11.6% Biomass, 10.6% Wind power, and 2.5%, while only 18.5% of electricity generation comes from non-renewable sources, such as natural gas, coal, and nuclear energy.

In line with current decarbonization trends, electricity grids are expected to progressively increase their share of renewable energy, which is expected to reduce the climate impacts of WE processes that use grid electricity as their main supply. Work by Lee et al. [41] estimates that the South Korean electricity mix could lower its life cycle emissions to 7.04 kg CO₂-eq/kg H₂ by 2050, following increased renewable energy adoption. Similarly, projected grid decarbonization in Germany could also reduce emissions to approximately 11.5 kg CO₂-eq/kg H₂ [8], while Spain is expected to reach values close to 7 kg CO₂-eq/kg H₂ by 2050 [48]. In the United States, work by Iyer et al. [53] projects a more moderate reduction, with grid-based electrolysis missions decreasing to circa 21 kg CO₂-eq/kg H₂ until 2041.

The global emissions of WE supplied via wind power are consistently shown in the literature as the lowest and most environmentally friendly pathway available [36]. Approximately 65% of the total emissions for wind energy production systems come from the construction phase, especially the steel and iron required for the towers and foundations rather than the hydrogen production process itself [34]. However, specific emission values can also depend on the efficiency of the electrolyzer and the geographical location. The lowest reported value was reported by Zhang et al. [32] with a value of 0.09 kg CO₂-eq/kg H₂ for hydrogen produced using onshore wind electricity coupled with PEMWE electrolysis. This article also evaluated two other technologies, AWE and SOEC, in onshore and offshore scenarios. Onshore wind turbine emissions were found to be nearly 10 times higher than offshore ones for the same electrolyzer technology. This difference is primarily attributed to corrosive marine environments, which require more material-intensive foundations and higher maintenance demand, resulting in increased related carbon footprints. Among the reviewed studies, the highest emissions related to wind-powered electrolysis in standard conditions were reported in Prasad and Khalid [39] with 2.04 kg CO₂-eq/kg H₂ for wind-powered PEMWE technology, possibly attributed to less clean electrical inputs during turbine production in India. In addition, some studies report even higher emission values under non-ideal or specific extraordinary variables due to suboptimal conditions, such as unfavorable geographical conditions affecting system performance, and reaching values of 4.34 CO₂-eq/kg H₂ [37]. Some other impact categories, such as freshwater ecotoxicity and carcinogenic human toxicity, can exhibit high values, as discussed by Hannouf et al. [45] due to upstream mining and processing of copper, steel, and cast iron for turbines.

The lowest global emission values provided by solar-based energy supplies were reported by Yadav and Banerjee [54] with emissions ranging from 1.03 to 1.87 kg CO₂-eq/kg H₂ for photovoltaic-based SOEC (PV-SOEC) and 1.05–1.67 kg CO₂-eq/kg H₂ for concentrated solar power SOEC (CSP-SOEC). The study was conducted in India, in a region characterized by some of the highest annual solar irradiation, which enables a higher level of hydrogen production relative to the carbon intensity associated with the infrastructure construction. In contrast, the highest values were presented by Zhang et al. [44] with Photovoltaic PEMWE (PV-PEMWE) power with values of 9.37 kg CO₂-eq/kg H₂ and Photothermal PEMWE (PT-PEMWE) with values of 8.67 kg CO₂-eq/kg H₂. This publication presented the highest values due to the high emissions released by the construction of the PV and PT power plants. Nearly 78% of the total emissions come from the construction of the PV power plant due to energy-intensive manufacturing of solar modules, including silica reduction, silicon purification, and ingot slicing. The PT powerplant represents

nearly 73% of total GHG emissions, with environmental impacts coming from metals and concrete usage, as well as the production of nitrate salts used in thermal energy storage. In solar-powered WE, similar to wind-powered WE, life-cycle emissions are largely concentrated in the construction phase, while operational emissions are near zero. These systems are characterized by a “front-loaded” environmental profile, primarily driven by the manufacturing of energy and electrolysis infrastructure. Consequently, extending plant lifetime and improving electrolyzer efficiency significantly reduce the GHG emissions per kilogram of hydrogen produced, resulting in very low average emissions over time despite the initial construction-related impacts [49].

For the elaboration of Figure 7, values were extracted from the reviewed articles and followed strict selection criteria to ensure consistent methodological comparability. Only studies that adopted a FU of 1 kg of hydrogen produced and used cradle-to-gate boundaries were considered. Prospective values were also not considered.

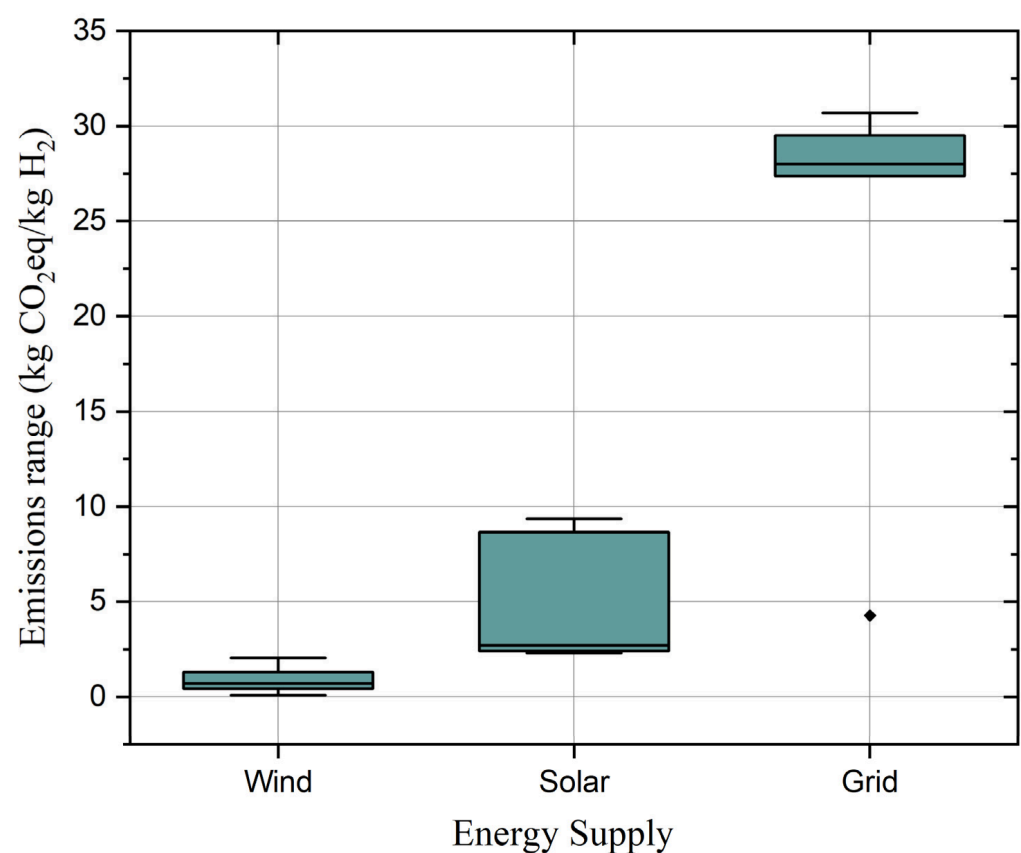


Figure 7. Distribution of emissions values across different electricity supplies.

Figure 7 further illustrates the distribution of global emission values across different electricity supplies, with wind-powered electrolysis reporting the lowest values and range of emissions, largely below 2 kg CO₂-eq/kg H₂, showing that this energy supply consistently exhibits low emissions across the literature, with values often related to lower operational, construction, and manufacturing emissions. Solar-powered electrolysis occupied an intermediate position, with values below 9.5 CO₂-eq/kg H₂, displaying a wider spread of global emission values that can be associated with higher infrastructure-related impacts compared to wind electrolysis, even if during the production of hydrogen, the emissions are near zero. In contrast, grid-based electrolysis shows the highest emission values, reaching values of 30.7 CO₂-eq/kg H₂, reflecting the carbon intensity of fossil-dominated electricity grid mixes [41,44,49].

These high values are mainly associated with electricity grids that still rely heavily on coal and natural gas, since the indirect emissions from electricity generation are transferred to the electrolysis process and dominate the total life cycle emissions. A noticeable exception can be observed in the form of a single value outlier corresponding to hydrogen production using the Brazilian electricity grid, which can be attributed to a predominantly renewable electricity mix [40]. This outlier reinforces the view that grid electricity should not be interpreted as a single consistent category, since its environmental performance depends strongly on the carbon intensity and renewable share of each national or regional electricity system.

5. Conclusions

Given the rapid expansion of the literature, a comprehensive assessment of publication trends and methodological practices is needed to provide a structured overview of the current state of knowledge and support the interpretation of reported environmental performance. The bibliometric analysis highlighted a pronounced growth in scientific publications addressing the LCA of hydrogen production via WE over the past decade, with a particularly sharp increase taking place from 2016 onwards. This temporal evolution reflects the rising relevance of WE studies within the field. The geographical distribution of publications shows a strong concentration of research activity in Europe, Asia, and North America, with China presenting the highest number of publications, indicating that WE LCA research is closely aligned with current decarbonization trends across a vast number of countries. In addition, the keyword co-occurrence analysis revealed a consolidation of research themes around WE in an LCA environment, suggesting a maturing and evolving research field. The most common keywords were “life cycle assessment”, “hydrogen production”, and “water electrolysis”.

The systematic review demonstrated a considerable degree of methodological consistency across the reviewed studies, with most articles sharing similar frameworks. This consistency is particularly evident in the definition of the FU, with 20 out of 23 studies employing 1 kg of hydrogen produced, facilitating cross-study comparability. Cradle-to-gate system boundaries were the most frequently applied, reflecting the dominant interest in earlier hydrogen production stages rather than downstream ones. Recipe and CML frameworks emerged as the most commonly used LCIA methods, and some studies did not adopt a well-defined framework, instead focusing mainly on emissions studies, with GWP, CI, and GHG assessment. For this reason, this impact category was by far the most extensively reported in the literature, with every publication implementing it in the analysis. Acidification, Ozone Depletion, and Human Toxicity/Health were also some of the most consistently included categories in the LCA analysis, even though presenting considerably less frequency in relation to GHG emissions.

Across bibliometric and systematic analysis, electricity supply emerges as the most influential factor shaping the environmental performance of hydrogen via WE. The reviewed studies consistently demonstrated that electricity consumption during the operational phase dominated total environmental impacts, which frequently accounted for the majority of global emissions reported in the literature. Differences in electricity generation mixes across different regions and countries resulted in a substantial variation in reported impact values, often exceeding the influence of electrolyzer technology choice or material composition. In this regard, renewable electricity sources, particularly wind and solar, are consistently associated with lower environmental impacts, in contrast to grid electricity, which, for most countries, is still composed of a high fossil fuel share, leading to significantly higher emissions. Future research should continue improving the methodological consistency of LCA studies by promoting greater harmonization in the definition of func-

tional units, system boundaries, and impact assessment methodologies, thereby facilitating more robust cross-study comparisons. In addition, the increasing decarbonization of electricity systems and the growing use of prospective electricity scenarios suggest that future LCA studies should further evaluate how evolving electricity mixes influence the long-term environmental performance of hydrogen production via water electrolysis.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157649/s1>, Table S1: List and characteristics of the included studies; PRISMA 2020 checklist [55].

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