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Review

On Green Hydrogen Generation Technologies: A Bibliometric Review

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Abstract: Green hydrogen, produced by water electrolysis with renewable energy, plays a crucial role in the revolution towards energy sustainability, and it is considered a key source of clean energy and efficient storage. Its ability to address the intermittency of renewable sources and its potential to decarbonize sectors that are difficult to electrify make it a strategic component in climate change mitigation. By using a method based on a bibliometric review of scientific publications, this paper represents a significant contribution to the emerging field of research on green hydrogen and provides a detailed review of electrolyzer technologies, identifying key areas for future research and technology development. The results reflect the immaturity of a technology which advances with different technical advancements, waiting to find the optimal technical solution that allows for its massive implementation as a source of green hydrogen generation. According to the results found in this article, alkaline (ALK) and proton exchange membrane (PEM) electrolyzers seem to be the ones that interest the scientific community the most. Similarly, in terms of regional analysis, Europe is clearly committed to green hydrogen, in view of the analysis of its scientific results on materials and electrolyzer capacity forecasts for 2030.

Keywords: green hydrogen; sustainability; renewable energy resources; sustainable development; bibliometric review; electrolyzers; technologies

Citation: Fernández-Arias, P.; Antón-Sancho, Á.; Lampropoulos, G.; Vergara, D. On Green Hydrogen Generation Technologies: A Bibliometric Review. *Appl. Sci.* **2024**, *14*, 2524. https://doi.org/10.3390/app14062524

Academic Editor: Hicham Idriss

Received: 5 February 2024
Revised: 8 March 2024
Accepted: 12 March 2024
Published: 17 March 2024

1. Introduction

Hydrogen, a ubiquitous chemical element in our universe, is emerging as a key energy carrier in the quest for a more sustainable and cleaner future [1]. This colorless gas is found in a variety of chemical compounds, with water (H_2O) being its most common form [2]. For decades, scientists and engineers have explored hydrogen's potential as a versatile and environmentally friendly energy source [3,4]. Its main attraction lies in its ability to store and release energy in the form of electricity and heat without generating greenhouse gas (GHG) emissions [5]. This characteristic makes it a promising alternative to fossil fuels and a key element in the transition to a decarbonized economy [6,7].

In terms of applications, hydrogen has multiple applications, from being a fuel for fuel cell vehicles and a stationary power source for backing up the electricity grid, to being a key component in the chemical and manufacturing industries. Its ability to store and transport energy efficiently makes it an ideal option for addressing intermittency issues in renewable energy generation and for powering sectors that are difficult to decarbonize. Some of the main advantages of hydrogen are as follows [8–10]:

- It is an important energy carrier, and when used as a fuel, it can be considered an alternative to the main fossil fuels, such as coal, crude oil, and natural gas, and their derivatives.
- It is a clean, reliable, and affordable source of energy and has the great advantage that the product of its combustion with oxygen is water, instead of CO and CO_2.

- It can be used directly in internal combustion reciprocating internal combustion engines, requiring relatively minor modifications if boosted to a moderately high pressure, as well as in turbines and boilers.
- It can be used in hydrogen/oxygen fuel cells to directly produce electricity. Again, the only product is H_2O.
- It can also be used in fuel cells with higher temperatures to generate electricity and heat simultaneously (as a cogeneration plant).

However, despite its advantages, the widespread adoption of hydrogen still poses significant technical challenges. Large-scale production of clean hydrogen is expensive, and its efficient storage and transport require advanced technologies. In addition, the infrastructure for its use in applications such as transportation is still under development in many places.

The hydrogen production process can be carried out from various energy sources. Several types of hydrogen can be distinguished (Figure 1), each with its unique characteristics and specific applications depending on its generation technology [11]:

- Green hydrogen is produced by a water electrolysis process using electricity from renewable sources, such as solar or wind energy. This water electrolysis process is completely clean, with no CO_2 emissions [12,13];
- Gray hydrogen is obtained from natural gas reforming, a process that emits CO_2. Although it is neither sustainable nor clean by itself, CO_2 capture technologies can reduce its emissions [14,15];
- Blue hydrogen is similar to gray in terms of its production from natural gas but differs in that CO_2 emissions are captured and stored rather than released into the atmosphere. This makes it a more sustainable option [16,17];
- Pink hydrogen is also known as synthetic hydrogen, and it is produced by electrolysis of water using nuclear energy. Although it is considered clean, its large-scale production presents regulatory and safety challenges [18];
- Yellow hydrogen is produced from the electrolysis of water using concentrated solar power (CSP) [19];
- Black hydrogen is generated from the combustion of coal; therefore, it is extremely polluting [20];
- Brown hydrogen is similar to black in terms of CO_2 emissions, and it is based on the combustion of lignite to generate hydrogen [21];
- Orange hydrogen is produced from emissions or waste from other sectors [22];
- White hydrogen is the one stored in subway reservoirs [23].

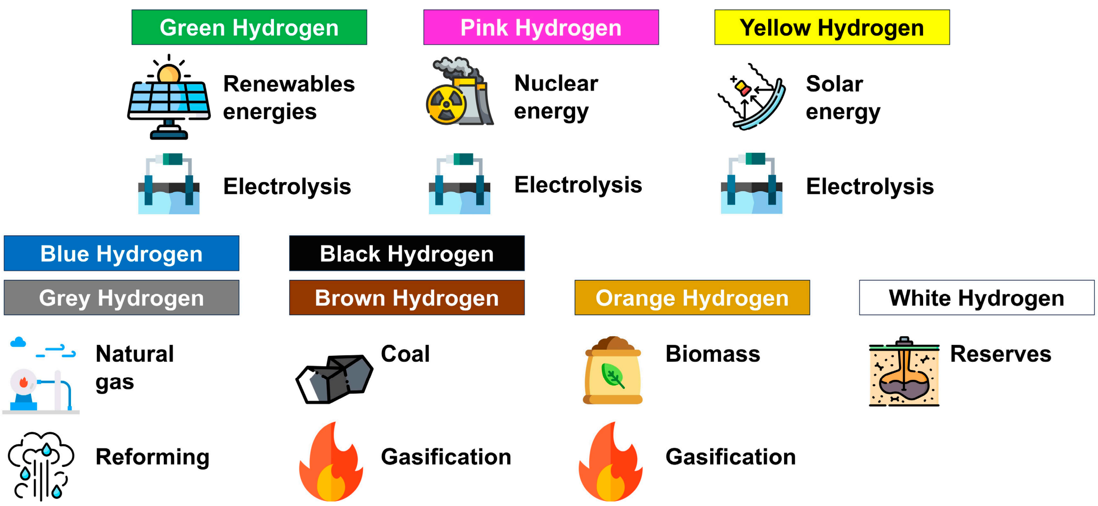

Figure 1. Hydrogen production methods, feedstock/electricity sources, and technology production.

A simple indicator of the interest that is shown in the different hydrogen generation technologies is the number of research papers including the term as the focus of the research (Figure 2). By searching in the Scopus database for related articles based on their title, abstract, or keywords (data collected in January 2024), the words of the different hydrogen generation technologies in the period between 1950 and 2023 reveal a clear reality. The number of results obtained for green hydrogen in this period is higher than 33,000, which means a rate of results close to 450 per year, while in the case of blue hydrogen technology, the number slightly exceeds 22,000 results, which means a rate of results close to 300 per year. For the rest of the technologies, only black and white hydrogen slightly exceed 10,000 results in the period of 1950–2023, with an obtained rate of results of less than 100 per year. For the rest of the hydrogen generation technologies, the results are even lower. In the period of 1950–2023, the results obtained for green hydrogen account for 35% of the total obtained results for all hydrogen generation technologies, while those obtained for blue hydrogen account for 23% of the total results. These two hydrogen generation technologies generate more than 50% of the research results obtained by the nine analyzed hydrogen generation technologies.

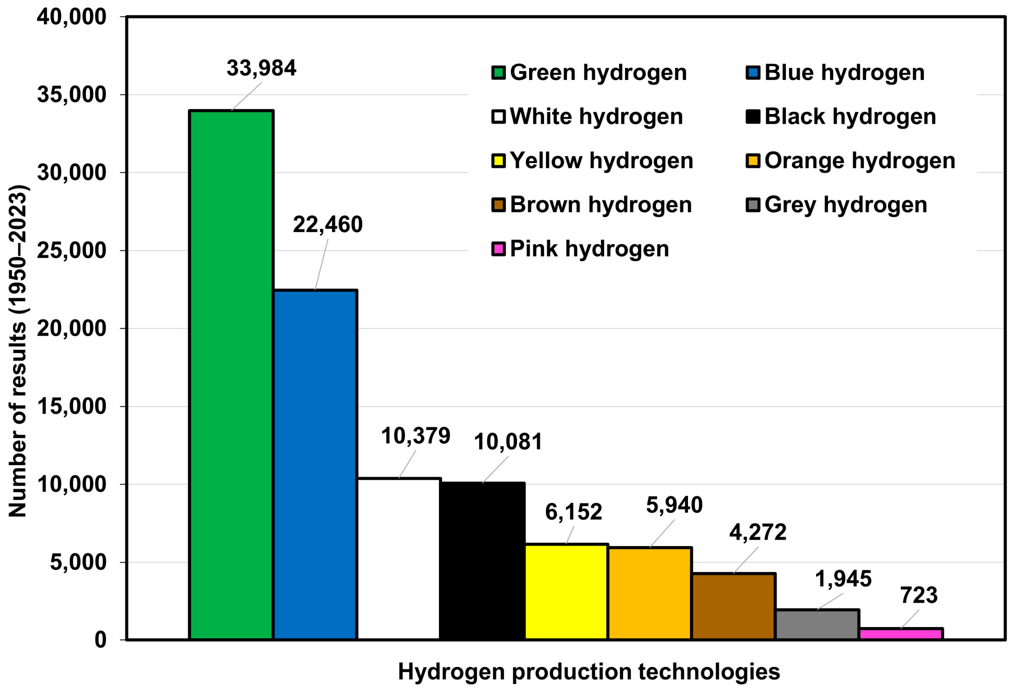

Figure 2. Results of the Scopus database search (data collected from the Scopus database in January 2024).

Based on the results obtained, green hydrogen has become a key pillar for the scientific community in the search for a cleaner and more sustainable energy grid. Its production is closely linked to renewable energy sources [24], which makes it highly desirable in the fight against climate change and the reduction in carbon emissions [25]. It has a wide variety of applications. It can be used as a fuel in fuel cells for electric vehicles, enabling clean, zero-emission mobility. It is also used in industrial applications to power production processes and as a stationary energy source to back up the power grid at times of high demand. In addition, it can be a source of clean heat for industrial and residential applications.

The production of green hydrogen is based on a process called water electrolysis. This process involves the decomposition of water (H_2O) into its basic components, hydrogen (H_2) and oxygen (O_2), using electricity. The electricity used in this process comes exclusively from renewable energy sources, such as solar panels or wind turbines [26]. This means that no greenhouse gases are emitted during the production of green hydrogen, making it a truly clean and sustainable energy source [27].

Electrolyzers are the fundamental components for using the electrical energy that is generated by renewable sources and subsequently generating hydrogen [28]. Currently, there are different types of electrolyzers, depending on their size and function, among which the following can be highlighted:

- Alkaline electrolyzers: these electrolyzers usually use an aqueous solution of potassium hydroxide as the electrolyte, and they are remarkable for their energy efficiency and low manufacturing cost [29,30];
- Proton exchange membrane (PEM) electrolyzers: these electrolyzers are very popular, and many modern electrolyzers are built with this technology. The electrolyte is a thin ion-conducting solid membrane used in place of the aqueous solution [31];
- Solid oxide electrolytic cells (SOECs): these are basically a corresponding fuel cell operating in reverse [32].

In this context, the objective of the present research is to analyze the state of the specialized literature on green hydrogen, its main generation technologies, as well as its fundamental applications. For this purpose, this work develops a bibliometric and technical review of the different green hydrogen generation technologies, as well as their applications. The motivation for combining a bibliometric review and a technical review is to help the scientific community identify the interest in the subject, as well as to help in the technical analysis of the different green hydrogen generation technologies.

2. Materials and Methods

In accordance with the research objective, a bibliometric review of the state of the specialized literature on green hydrogen, its main generation technologies, as well as its fundamental applications has been carried out. For this purpose, this work develops a bibliometric review of the different green hydrogen generation technologies, as well as their applications. The motivation for combining a bibliometric review and a technical review is to help the scientific community identify the interest in the topic, as well as to help in the technical analysis of the different green hydrogen generation technologies.

The formulation of objectives (Phase I, Figure 3) was developed in the introduction. The bibliometric analysis (Phase II, Figure 3) was performed in the selected bibliographic database, Scopus, since it is a database of international relevance, which in addition to collecting bibliographic information analyzes the behavior of citations that are received by the journals and from these data, it generates a large number of bibliometric indicators [33,34].

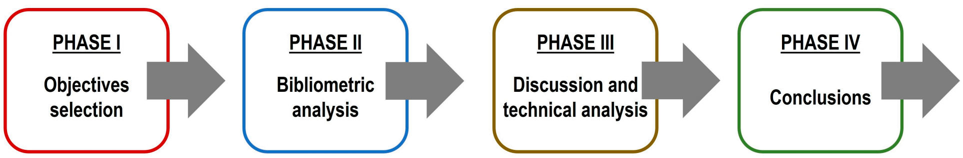

Figure 3. Scientific methodology outline.

To search for related documents in the academic databases, a complex keyword search string, which is a combination of text, numbers, and sometimes special characters that a user enters to obtain specific results, is required. In the context of this study, to search in the Scopus database, the search query addressed the article record, including the title, abstract, and keywords, but not the full text. Moreover, to ensure a comprehensive search and that the articles that were most relevant to the topic would be identified in the Scopus database, several keywords were incorporated, along with a combination of Boolean operators (e.g., AND, OR, etc.). Table 1 details the search string used to query the Scopus database.

Table 1. Search string for Scopus database.

Search String
TITLE-ABS-KEY ((“hydrogen”) AND (“production” OR “energy” OR “generation”) AND (“generator” OR “electrolysis” OR “electrolyzer” OR “proton exchange membrane” OR “PEM”) AND (“renewable” OR “green”) AND (“solar” OR “photovoltaic”) AND (“state of the art” OR “review” OR “revision” OR “overview”))

Subsequently, after applying the search criteria, the articles were retrieved and processed. The VOSviewer® software 1.6.16, which allows for a graphical preview of the data using category maps [35,36], was used to analyze the data. Specifically, the following analyses were performed: (i) annual trend of publications on the subject; (ii) most relevant types of sources; (iii) most relevant sources; (iv) most relevant areas; (v) co-authorship network; (vi) production between countries; and (vii) keyword and co-citation trends. The acronyms and nomenclatures employed in the text are summarized at the end of the document in Nomenclature at the back matter.

3. Results

This section shows the results that were obtained in the performed bibliometric analysis (Phase II, Figure 3). The first study identified in Scopus on green hydrogen was conducted by Coiante et al. [37] in 1992. This article questioned the photovoltaic technology as a source of efficient electric power generation and for the first time raised the possibility of connecting a H_2 storage system to a photovoltaic installation. Figure 4 below shows the annual trend of publications on this topic, generated from the Scopus sample of 302 results (Figure 5). Two clear periods are observed in this publication trend: Stage I, from 1993 to 2010; and Stage II, from 2011 to 2023. This trend change after 2011 is also in line with the evolution proposed by the International Energy Agency (IEA) to achieve a global production of around 8 million tons of hydrogen per year in 2030 from low-emission sources, which means obtaining around 350 thousand tons in 2023 [38,39].

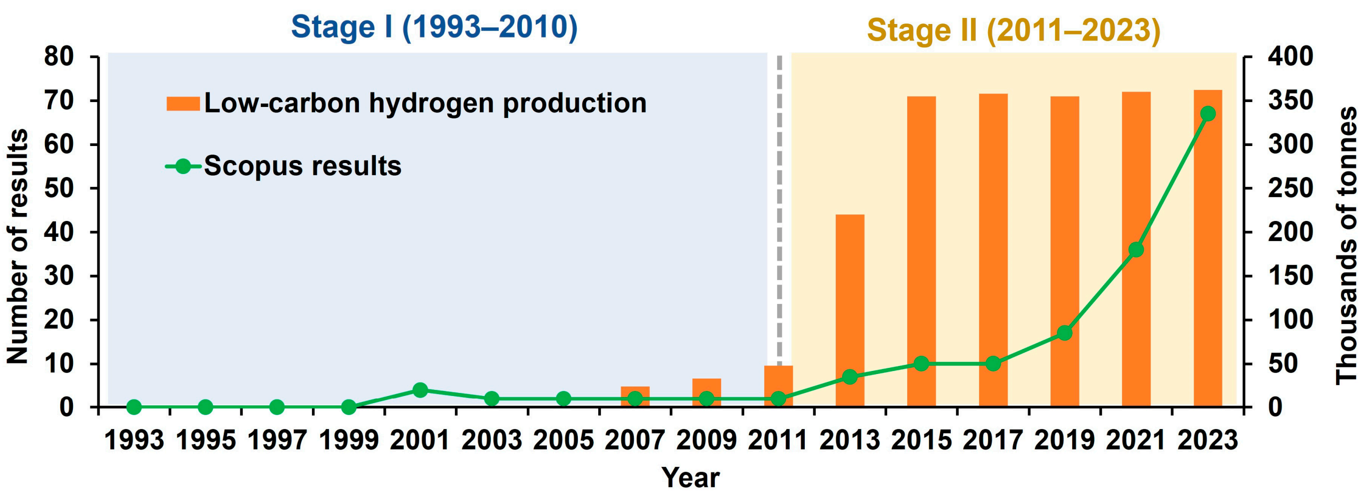

Figure 4. Green hydrogen publications by year (1993–2023) (data collected from Scopus database in January 2024 and from the Global Hydrogen Review 2023 [38]).

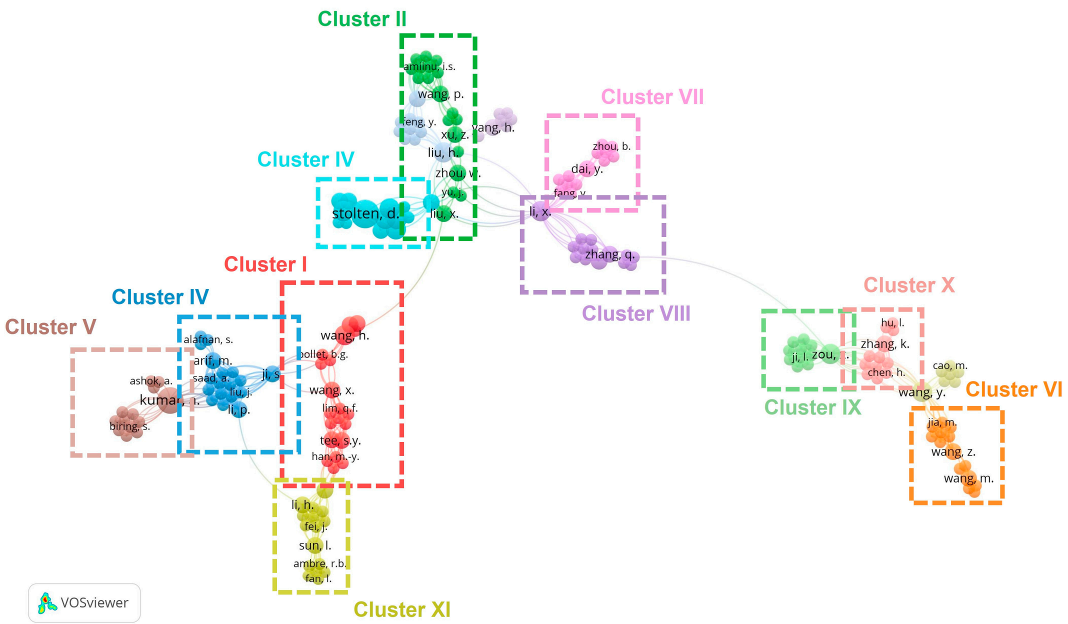

Figure 5. Green Hydrogen results by co-authorship network (1993–2023) (data collected from Scopus database in January 2024). Source: developed by the authors in VOS Viewer software 1.6.16.

In terms of annual productivity, between 1993 and 2010, the interest in green hydrogen by the scientific community was very low, with the results/year indicator being 0 in most years of this period. The year 2001 stand out when the values were four results/year, respectively. From 2011 onwards, there was a slight interest on the part of the scientific community, based on the results obtained, which were close to 10 results/year in the period of 2011–2017. From the year 2017, an exponential increase of interest in green hydrogen occurred in the scientific community, going from 10 results per year in the year 2010 to almost 70 results per year in the year 2023. This means an average of 32.5 results per year in the period of 2017–2023.

Of the 302 results obtained, 237 were published in journals (Table 2), while 32 were published in conference proceedings, 24 in books, and 9 in book series. Therefore, 89% of the results obtained in the search used the first two source types.

Table 2. Green hydrogen result distribution by source type (1993–2023) (data collected from Scopus database in January 2024).

Source Type	Number	Percentage
Journal	237	78.48%
Conference Proceeding	32	10.60%
Book	24	7.95%
Book Series	9	2.98%

The most influential source in Scopus on green hydrogen is the *International Journal of Hydrogen Energy* with 27 (8.94% of the total) of the obtained results published in it. The second most influential source is *Energies*, with 19 results (6.29% of the total). The podium is completed by the *Chemical Society Review* with 12 results (3.97% of the total). The rest of the sources have several obtained results, all less than 10. It can be seen, therefore, that green hydrogen, as a research area, is very diversified, with no preferential sources when it comes to publishing relevant results in the scientific community. Of the 302 results obtained, Table 3 below shows the results obtained by the most relevant sources.

Table 3. Green hydrogen result distribution by source title (1993–2023) (data collected from Scopus database in January 2024).

Ranking	Source Title	Number	Percentage
1	*International Journal of Hydrogen Energy*	27	8.94%
2	*Energies*	19	6.29%
3	*Chemical Society Reviews*	12	3.97%
4	High level radioactive waste management (Conference)	6	1.99%
5	*Journal Of Cleaner Production*	5	1.66%

On the other hand, the 302 articles are divided into 21 areas, with the Top 5 introduced in Table 4. The category "Energy" is the main category, with 169 associated results (55.96% of the total). The second category with the most associated results is "Engineering" with 109 results (36.09% of the total). And the third place goes to "Chemistry" with 65 results (21.52% of the total). Note that some results may have more than one subject area. Energy and Engineering account for more than 90% of the results.

Table 4. Number of publications by area (1993–2023) (data collected from Scopus database in January 2024).

R	Area	Results	Percentage
1	Energy	169	55.96%
2	Engineering	109	36.09%
3	Chemistry	65	21.52%
4	Materials Science	57	18.87%
5	Chemical Engineering	54	17.88%

Figure 4 below shows the co-authorship network of authors. The eleven most representative clusters of the network were identified. All authors who are present in the network achieve their co-authorship link from the year 2016, when green hydrogen technology emerged as a future source of electric power generation. As for the authors, Stolten (Cluster IV, cyan) and Kumar (Cluster V, brown) are the most influential authors in the field, taking into account that with six and five results, respectively, they achieve a total link strength that is close to 30.

However, if the analysis of the co-authorship network of authors is carried out as a function of time (Figure 6), it can be observed that Stolten and Kumar have lost influence from 2016 onwards, and since then, authors such as Li, Liu, and Wang have gained influence. It is also possible to observe how the only cluster with influence prior to 2016 is Cluster IV, represented by Solten, while Kumar continues to be a reference for later authors.

By analyzing the authors' affiliation by country, it is observed that this research topic is global, since the 302 articles that are part of the sample are distributed in more than 50 countries. Figure 7 represents the network of the most represented countries of affiliation. According to the data obtained, China, with 56 documents and 8990 citations; India, with 34 documents and 1239 citations; and the United States, with 33 documents and 7250 citations are the countries with the highest number of results generated. Other well-positioned countries are the European countries—the United Kingdom, Germany, and Italy—as well as the Asian countries—Saudi Arabia, Malaysia, and South Korea. Canada and Australia also play an important role in terms of country of affiliation.

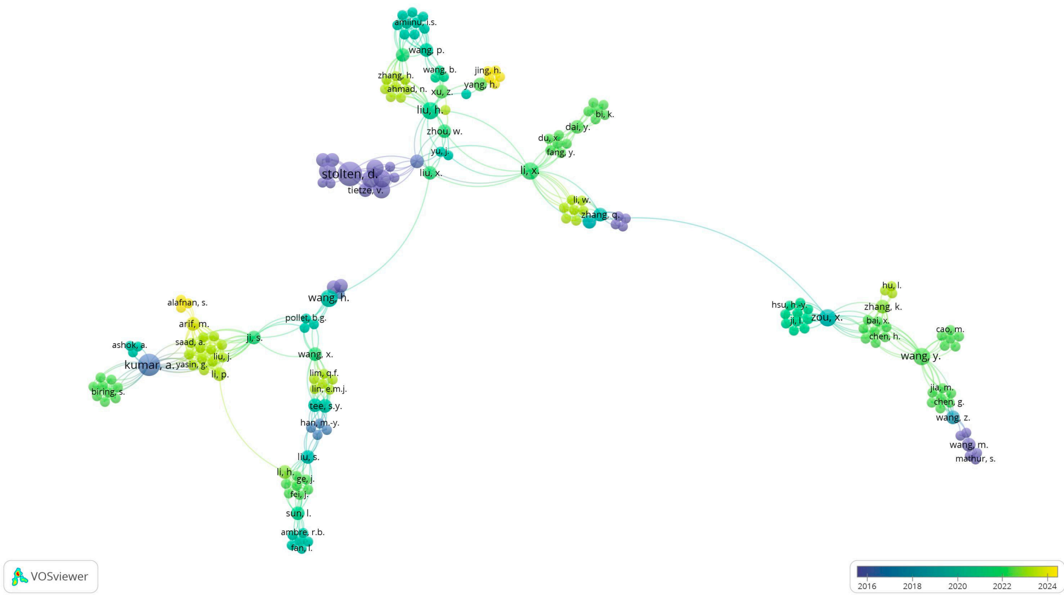

Figure 6. Green hydrogen results by co-authorship network, time-based (1993–2023) (data collected from Scopus database in January 2024). Source: developed by the authors in VOS Viewer software 1.6.16.

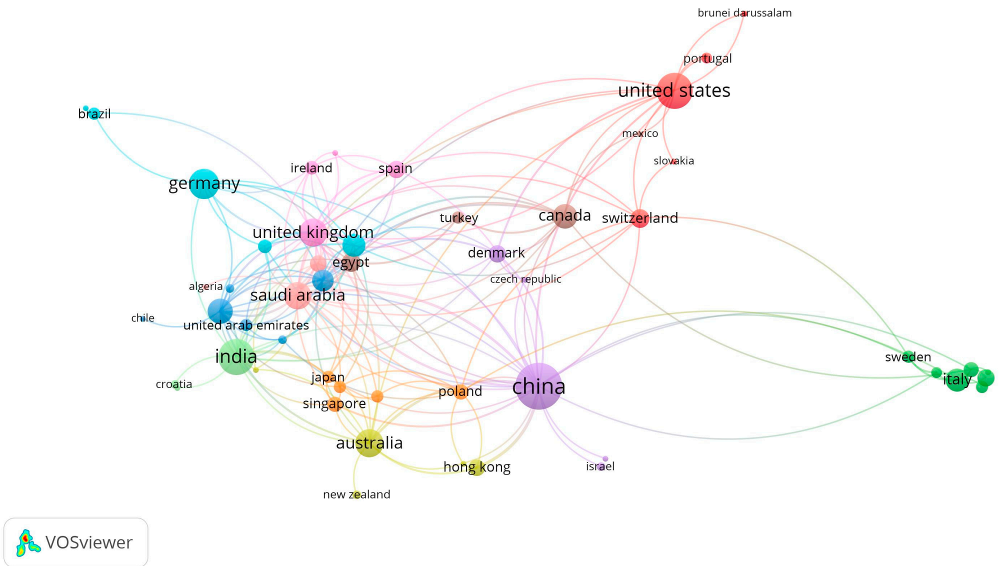

Figure 7. Green hydrogen results by authors' affiliation by country (1993–2023) (data collected from Scopus database in January 2024). Source: developed by the authors in VOS Viewer software 1.6.16.

In the case of the keyword co-occurrence network (Figure 8), different clusters can be observed. Cluster I (red), with 54 keywords, includes relevant keywords such as "hydrogen production" (159 occurrences, 2626 total link strength), "solar power generation" (145 occurrences, 2474 total link strength). In Cluster II (dark green), there are 47 keywords of low relevance. In Cluster III (yellow), 37 keywords are grouped, among which "hydrogen storage" (69 occurrences, 1352 total link strength) and "renewables energies" (55 occurrences, 1023 total link strength) stand out. Cluster IV (orange) has 28 keywords of low relevance. In Cluster V (purple), there are 25 keywords, among which "fossil fuels" (66 occurrences, 1310 total link strength) and "carbon dioxide" (31 occurrences, 781 total link strength) stand out. Finally, Cluster VI (cyan) groups 14 keywords of low relevance.

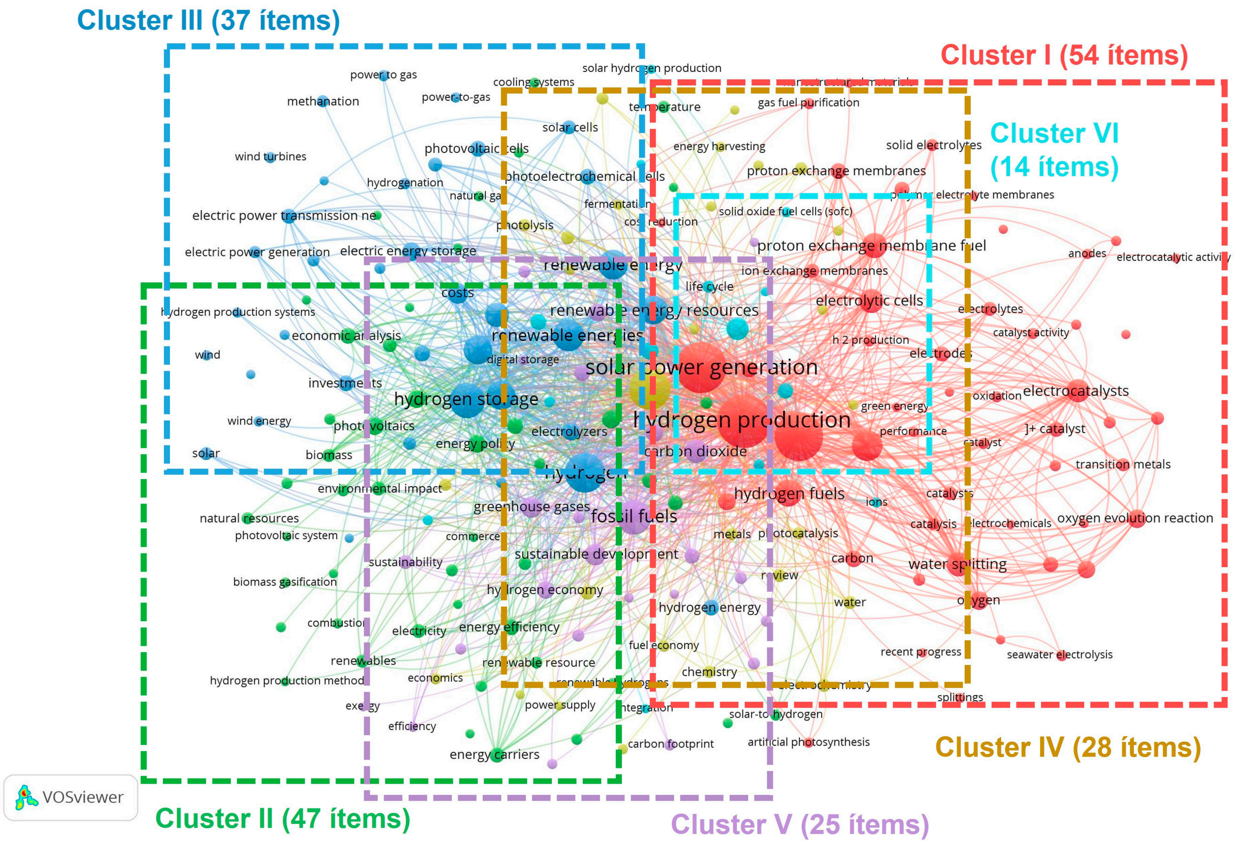

Figure 8. Keyword trends and cluster's structure (1993–2023). Source: developed by the authors in VOS Viewer software 1.6.16.

4. Discussion

Renewable energy resources play a vital role in achieving sustainable development and can have significant social, environmental, and economic impacts [40–42]. Although there are suggestions and strategies to reduce energy consumption and demand, there are still several open challenges that must be addressed [43]. As a result, the demand for energy has been increasing at a global scale [44,45]. Green hydrogen has the potential to transform the production of energy in various domains [46] across countries [47] while helping to achieve a green future, a renewable energy society, and sustainable development goals [12,48,49]. As a field, green hydrogen is advancing rapidly [50–52]. However, open issues, concerns, and challenges remain that must be overcome [53–55].

Due to its interdisciplinary nature and its ability to transform various sectors, green energy is being examined from multiple perspectives and across domains. As the research around this important topic increases, it is essential to have a mapping of the existing literature to get a better understanding of the topic and the research that has been conducted regarding it, so that research gaps can be identified and examined in future studies to further advance the topic. To aid in this effort, this study involved the conduct of a bibliometric and technical review of the existing literature. Specifically, the study identified and analyzed 302 documents from the Scopus database.

Based on the findings, although it has been over three decades since the first related document that was identified was published, the number of related documents being published started to increase since 2017, showcasing a drastic increase in published documents during the last few years (2020–2023). This fact highlights the shift to more sustainable approaches, as well as the interest in using renewable energy resources and striving for a greener and more sustainable future. Moreover, the documents of the examined collection were published in different sources, such as journals, conferences, books, etc. Most studies were published in journals, which highlights the high quality and in-depth analysis of the studies, as well as the importance of the topic examined. It is also worth noting that among the most impactful sources based on the total number of related documents published on this topic, different types of sources and from different publishers arose. The *International Journal of Hydrogen Energy*, *Energies*, and *Chemical Society Reviews* emerged as the three most impactful sources.

Furthermore, as green hydrogen can be applied in various domains, it was important to examine the areas in which current research is mostly focused. Based on the findings, most of the studies put emphasis on examining the role of green hydrogen in the context of energy or engineering. Studies also examine green energy in areas such as chemistry, material science, and chemical engineering, but to a lesser extent. This fact further validates the interdisciplinary nature of green hydrogen and its potential to transform different sectors. However, there is a clear need to further examine its role and implications in other key areas as well. Its interdisciplinary and multidisciplinary nature, as well as the significance of its being examined from different dimensions, are further highlighted based on the 10 clusters that emerged in the co-authorship network. Clusters IV and V showcased the highest link strength, which was close to 30, with Stolten and Kumar being the most influential authors in these two clusters, respectively. When analyzing the co-authorship network as a function of time, since 2016, which was around the time period in which the number of published documents on this topic increased exponentially, authors such as Li, Liu, and Wang have gained significant influence. It is worth noting that in contrast to Cluster V, which is the only main cluster with influence prior to 2016, Cluster IV still continues to provide a common reference point to more recent studies.

The significance of adopting and implementing green hydrogen and the global interest that it attracts can be justified by the fact that the examined documents originate from authors from more than 50 different countries. China, India, and the United States emerged as the countries whose authors, based on their affiliation, published the most documents and received many citations. However, significant contributions have also been made by other countries, including the United Kingdom, Germany, Italy, Saudi Arabia, Malaysia, South Korea, Canada, and Australia. Although authors from various countries contributed studies on this topic, there is a clear lack of more international collaborations to further examine and advance the topic. Finally, when looking into the keyword co-occurrence network, a total of six clusters emerged. Keyword Clusters II, IV, and VI emerged as having a lower relevance, as they depicted a weaker link strength. On the contrary, keyword Clusters I, III, and V arose as the most impactful ones, as they represented the highest link strength. The three most impactful keyword clusters were associated with keywords such as "hydrogen production" and "solar power generation" (Cluster I), "hydrogen storage" and "renewable energies" (Cluster III), as well as "fossil fuels" and "carbon dioxide" (Cluster V).

The analysis of regions regarded China, the United States, Europe, and the rest of the world (RoW) as regions and focused on four variables (Figure 9): (i) electrolyzer capacity 2023 (GW); (ii) announced electrolyzer capacity 2030; (iii) research results; and (iv) citation results. Based on the results, it is possible to see how the region with the most research results is Europe, followed by the rest of the world. These regions are also the ones that have the greatest citation impact of their research, in addition to being the ones that have the most electrolyzer capacity in the year 2023, and it is expected that this will remain the same in the year 2030 according to the IAE estimate [39]. Europe is expected to reach approximately 110 GW of electrolyzer power, while the rest of the world will exceed 360 GW. On the other hand, China and the United States have not significantly developed their electrolyzer capacity up to now and do not plan to do so in the 2030 horizon, with their forecast capacity being less than 50 GW.

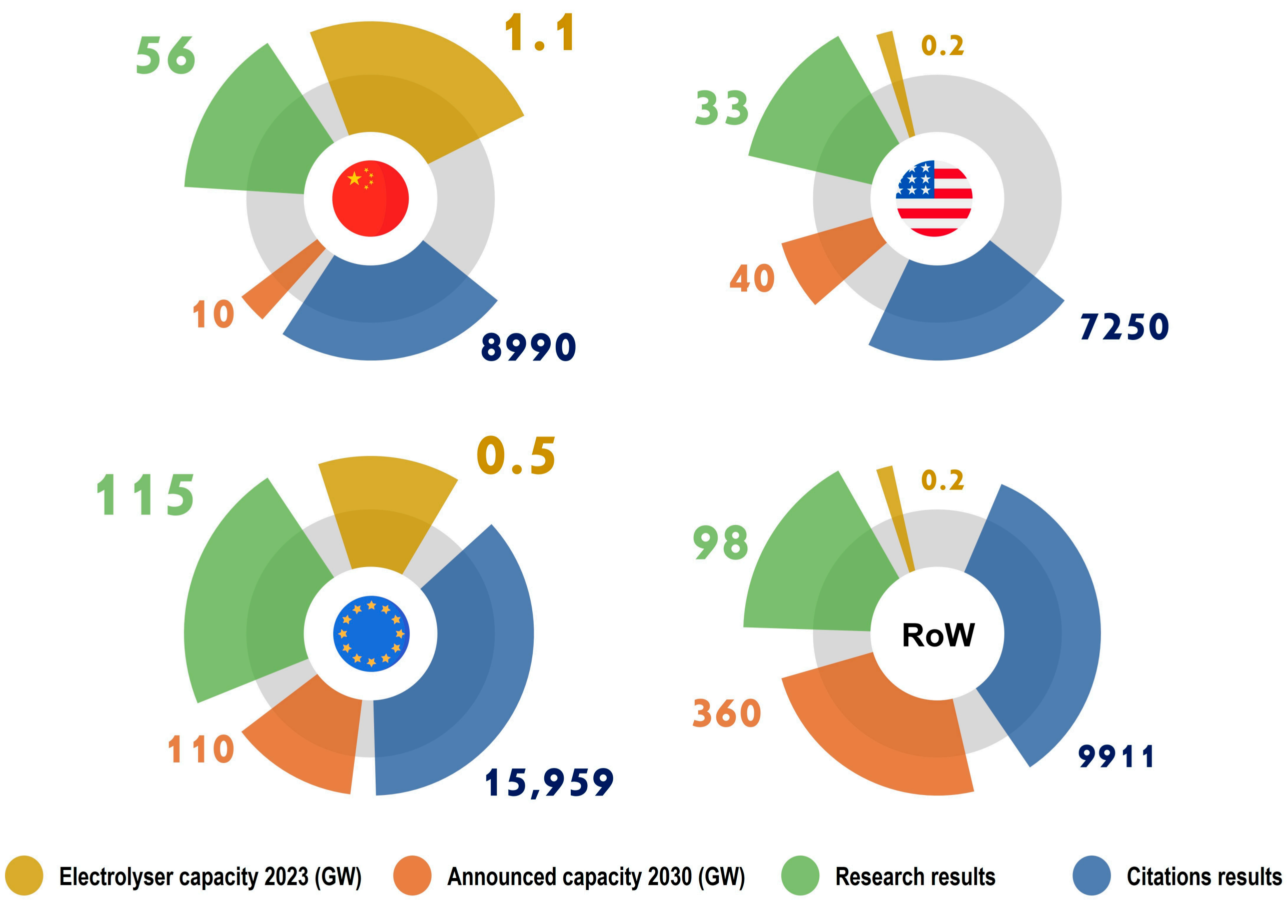

Figure 9. International comparison of different variables around green hydrogen (data collected from Scopus database in January 2024 and from the Global Hydrogen Review 2023 [38]).

If the keyword analysis is carried out based on the identified time periods (Figure 3) 1993–2010 (Stage I) and 2011–2023 (Stage II), it is possible to observe significant differences (Figure 10). In the period of 1993–2010 (25 results), there was a greater dispersion of keywords and, therefore, there was a lower co-citation link among them, in view of the size of the graph and the long length of the lines. In addition, there are more representative keywords, such as "hydrogen", "solar energy", or "hydrogen production", in view of the larger size of their circles. On the other hand, in the graph obtained in Stage II (277 results), the keywords are more closely linked, which shows that there is a greater co-citation link among them and that, therefore, they are more frequently used in conjunction. Regarding the number of citations, it is observed that there are keywords, such as "hydrogen production", "solar energy", and "hydrogen storage", with larger circles, which shows that the number of times these words are used is higher.

If the analysis of keywords based on time periods is carried out quantitatively, considering the 10 most used keywords, relevant results are obtained. Among the documents of Stage I (1993–2010) (Table 5), the keyword with the highest occurrence is "hydrogen", followed by the words "solar energy", which appear in more than 60% of the 25 results that were published in this period of time. At the same time, these words are the ones with the highest total link strength; therefore, they appear to a greater extent together with other relevant keywords.

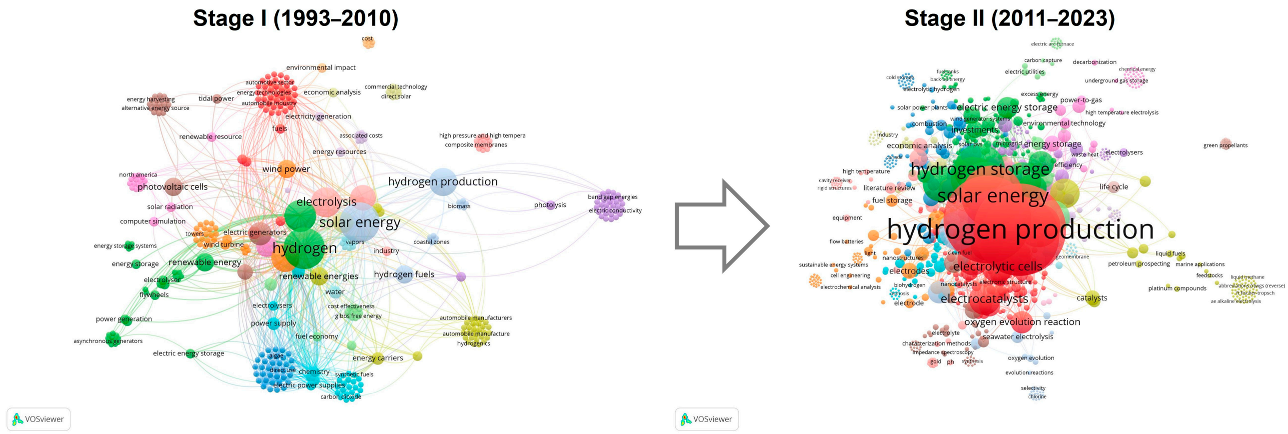

Figure 10. Keyword trends (1993–2010 and 2011–2023). Source: developed by the authors in VOS Viewer software 1.6.16.

Table 5. Most frequently used keywords in Stage I (1993–2010).

Keyword	Occurrences	Occurrences (%)	Total Link Strength
hydrogen	16	64.0%	349
solar energy	15	60.0%	385
renewable energy resources	11	44.0%	221
electrolysis	10	40.0%	194
fuel cells	9	36.0%	221
hydrogen production	9	36.0%	176
solar power generation	8	32.0%	224
hydrogen storage	7	28.0%	245
electricity	6	24.0%	226
fossil fuels	6	24.0%	198

On the other hand, when carrying out the same analysis of the documents that were published in Stage II (2011–2023), it is observed that the most used keywords are “hydrogen production” and “solar power generation” (Table 6). All words in this period have a reduced percentage of occurrence compared to the results obtained in the period of 1993–2010. This is due to the greater number of keywords that were identified in Stage II compared to those identified in Stage I. Of the 10 most used words in both periods, 7 are repeated in both periods: hydrogen, hydrogen production, hydrogen storage, solar energy, solar power generation, electrolysis, and fossil fuels. These results demonstrate that since the beginning of research in green hydrogen, there has been a trend on the part of the scientific community toward hydrogen, electrolysis as a method of generating green hydrogen, as well as solar energy and fossil fuels as the sources of electrical energy generation.

Table 6. Most frequently used keywords in Stage II (2011–2023).

Keyword	Occurrences	Occurrences (%)	Total Link Strength
hydrogen production	142	51.3%	2405
solar power generation	132	47.7%	2278
electrolysis	115	41.5%	2056
solar energy	80	28.9%	1446
hydrogen	70	25.3%	1338
hydrogen storage	61	22.0%	1234
fossil fuels	60	21.7%	1210
renewable energies	50	18.1%	895
water electrolysis	49	17.7%	918
renewable energy	43	15.5%	718

The large-scale production of green hydrogen faces major challenges that must be overcome [50,56]. Among these challenges, it is possible to identify the following (Table 7): (i) limited infrastructure; (ii) low electrolysis efficiency; (iii) high technical complexity in storage and transport; (iv) economic feasibility; and (v) environmental impact, as the technological development of green hydrogen implies some environmental impact, as well as the consumption of sometimes scarce material resources. After the first search in the Scopus database (Table 1), additional search fields were added to identify the importance of these challenges for the scientific community.

Table 7. Main challenges facing large-scale green hydrogen generation.

Challenge	Description	Added Search Field	Number Results (%)	References
Limited infrastructure	In the various key stages of green hydrogen—production, storage, and distribution—high financial investments are needed to develop an infrastructure that is currently in an early stage of development.	AND ("infrastru*" OR "develop*" OR "facilities" OR "instala*")	189 (62.5%)	[50,57]
Low electrolysis efficiency	Although it has improved, electrolysis faces major challenges in terms of energy efficiency. Improving the effectiveness of electrolyzers is critical to making green hydrogen production more sustainable.	AND ("efficien*" OR "abili*" OR "capabili*" OR "producti*")	285 (94.3%)	[58–63]
High technical complexity in storage and transport	Hydrogen is a difficult gas to store and transport efficiently. Advances in advanced storage technologies and safe and efficient transportation systems are needed.	AND ("storage*" OR "distribu*" OR "transpor*")	156 (51.6%)	[64,65]
Economic viability	Although production costs have decreased, they are still relatively high compared to other technologies. Green hydrogen must be positioned from the point of view of economic profitability compared to other technologies such as gray hydrogen.	AND ("econo*" OR "viabi*" OR "valid*" OR "habili*")	125 (41.4%)	[58,62]
Environmental impact	The development of this technology implies a certain environmental impact, as well as the consumption of sometimes scarce material resources.	AND ("enviro*" OR "ecolo*" OR "impact" OR "natural")	149 (49.3%)	[66]

In view of the results obtained in this bibliometric review, it can be seen that these challenges, which are identified by some authors, are also relevant for the rest of the scientific community, with aspects related to them appearing in more than 50% of the obtained results. The first of these challenges (Table 7) is the limited infrastructure for green hydrogen production, which poses significant challenges that must be addressed to realize its potential as a sustainable energy vector [57]. First, the lack of large-scale production facilities hinders the ability to meet the growing demand for green hydrogen. Expansion of these facilities is essential to take advantage of the abundance of renewable sources and meet the needs of diverse applications, from mobility to heavy industry.

On the other hand, the efficiency of electrolysis should also be analyzed (Table 7). Electrolysis is one of the simplest processes for creating hydrogen from water. However, since it is an endothermic reaction, it requires a high energy input of electricity to be produced. It is a process in which electrical energy is converted into chemical energy in the form of H_2 and O_2 as a by-product. Two reactions take place at each electrode (anode and cathode) [58]. Water splits when electricity is applied, producing H_2 at the cathode and O_2 at the anode through the following reactions:

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

According to this equation, two H_2 molecules are needed for each H_2O molecule. Therefore, the ideal molar ratio of hydrogen to water in electrolysis is 2:1. However, in practice, the efficiency of electrolysis can vary depending on different factors.

The molar mass of H_2O is 18 g/mol and that of H_2 is 1 g/mol, and 1 mole of H_2O is expected to produce 2 moles of H_2. In terms of mass, 18 g of H_2O could be expected to produce approximately 2 g of H_2 (considering that the density of hydrogen is approximately 0.0899 g/L at standard conditions). Therefore, under ideal conditions, 39 kWh of electricity and 8.9 L of water (H_2O) are required to produce 1 kg of hydrogen H_2 at 25 C and 1 atmosphere pressure [59]. If a hydrogen fuel cell consumes about 0.9 kg/100 km [60], about 48 L of water (H_2O) would be needed to cover 600 km under ideal conditions. Considering that it would take around 36–60 L of fossil fuels to cover this distance, it is very unlikely at this stage that hydrogen can replace fossil fuels as a vehicle fuel.

A separator between the anode and cathode electrodes ensures that the products remain segregated. In the different electrolyzer technologies, the most relevant differences are found in (Figure 11) (i) the separator located between the two electrodes and its function; and (ii) the way of introducing the initial product (H_2O) and segregating the obtained products (H_2 and O_2). These differences drastically influence the way in which chemical reactions take place both at the anode and the cathode.

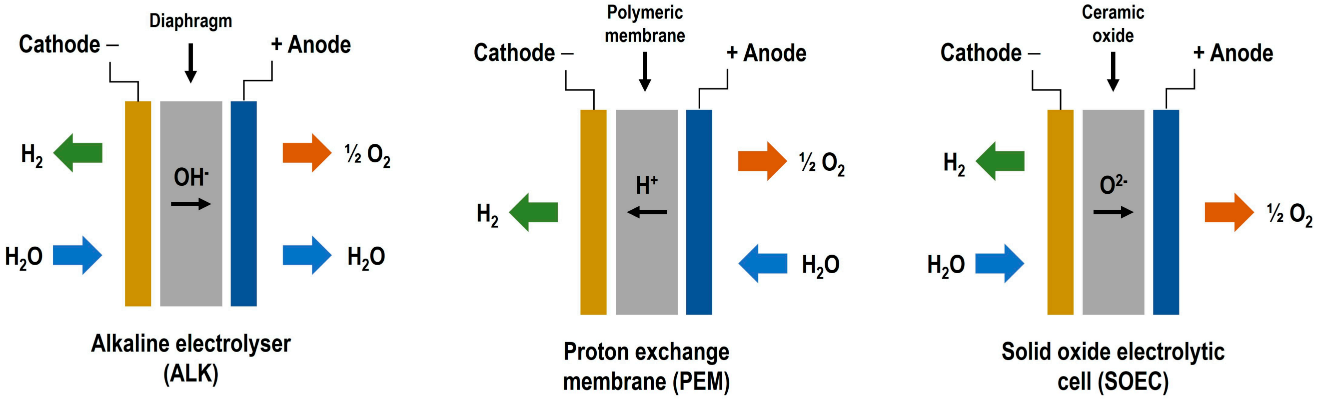

Figure 11. Schematic diagram of operating principle of different electrolyzer technologies to obtain green hydrogen.

In the case of an alkaline electrolyzer (ALK), water enters the cathode and separates into hydrogen (H^+) and hydroxide ions (OH^-). These hydroxide ions travel through the electrolyte to the anode, where they are reduced to form gaseous oxygen molecules. The efficiency of this process is influenced by several factors, such as the quality of the materials used, the temperature, and the pressure. Although the ALK electrolyzer has traditionally been more suitable for stationary applications due to its slower response to changes in load, continuous improvements are expanding its viability in more dynamic applications:

$$\begin{array}{c} \text{Cathode}: \ 2H_2O\ (l) + 2e^- \rightarrow H_2(g) + 2OH^- \\ \text{Anode}: \ 2OH^-\ (aq) \rightarrow 1/2\, O_2(g) + H_2O(l) + 4e^- \end{array} \quad (2)$$

In the case of proton exchange membrane (PEM) electrolyzers, water is injected into the anode, where it is split into protons (H^+) and oxygen molecules (O_2). The protons (H^+) pass through the membrane to the cathode to generate hydrogen (H_2):

$$\begin{array}{c}\text{Anode}: \ H_2O\ (l) \rightarrow 2H^+(g) + {}^1\!/\!_2\, O_2 + 2e^- \\ \text{Cathode}: \ 2H^+(g) + 2e^- \rightarrow H_2\end{array} \tag{3}$$

Finally, in the case of solid oxide electrolysis cell (SOEC) electrolyzers [65], as in ALK electrolyzers, water enters the cathode and is split into hydrogen (H+); however, unlike ALK, oxygen anions ($O_2{}^-$) are produced at the cathode. These anions pass through the solid oxide or ceramic electrolyte to produce oxygen (O_2) molecules at the anode:

$$\begin{array}{c}\text{Cathode}: \ H_2O\ (l) + 2e^- \rightarrow H_2(g) + O^{2-} \\ \text{Anode}: \ O^{2-} \rightarrow {}^1\!/\!_2\, O_2(g) + 2e^-\end{array} \tag{4}$$

ALK electrolyzers are the most widely used at present [63]. In view of the results obtained in the present research (Figure 12), the alkaline electrolyzer (ALK) and proton exchange membrane (PEM), which both had over 90 occurrences, meaning that they appear in more than 40% of the results obtained, are the ones that generate the most interest in the scientific community. Finally, solid oxide electrolytic cell (SOEC) electrolyzers are only investigated in a minority of studies, obtaining only 21 results, therefore appearing in less than 10% of the results obtained.

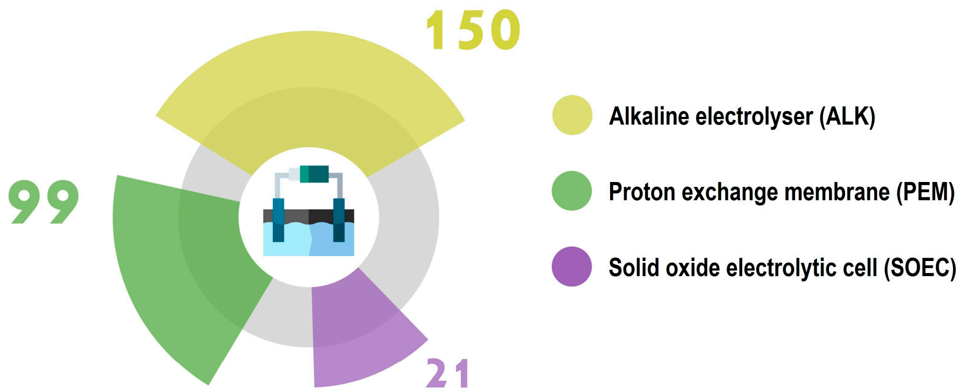

Figure 12. International comparison of research results of different electrolyzer technologies to obtain green hydrogen (data collected from Scopus database in January 2024).

The need for a sufficiently sized and safe transportation and storage network is essential to ensure a successful transition (Table 7). Among the various storage techniques, the injection of green hydrogen into depleted fossil hydrocarbon reservoirs [65], as well as storage as a compressed gas and processing the hydrogen into another more stable substance, such as ammonia, are positioned as viable techniques.

The cost of green hydrogen has decreased significantly, making it competitive with other technologies (Table 7). The cost of H_2 production from PEM electrolyzers is around 9 USD/kgH_2, and it is also the most environmentally friendly electrolysis process, emitting the lowest GWP per kg H_2 produced (1.0 kg CO_2/kg H_2) [62]. However, many researchers question the role of hydrogen in decarbonizing economies and propose as an alternative to see a huge role for gas [67].

Finally, when taking the scope of this study into account, the use of only one database to identify the related documents, despite it being highly regarded and widely used, can be considered the main limitation of this study. Additionally, the study investigated an analysis of the existing literature following a bibliometric analysis and scientific mapping approach. Therefore, future studies should focus on systematically examining the adoption and implementation of green hydrogen in specific domains, so that more particular findings to each sector can emerge. Although green hydrogen has the potential to drastically transform different domains and help achieve a greener and more sustainable future, the research into this topic is still in its infancy. There is a clear need for more common guidelines and standards to be developed and for more case studies to take place.

5. Conclusions

Green hydrogen is emerging as a key building block in the transformation toward a more sustainable and decarbonized energy landscape. Its ability to efficiently store renewable energy and its versatility in industrial and transport applications open the door to innovative solutions to energy and environmental challenges. Moreover, being produced from renewable sources, green hydrogen offers a clean and emission-free alternative to fossil fuels, thus addressing the urgency of reducing greenhouse gas emissions. Its potential to internationalize energy and foster economic development and job creation underlines its role as a catalyst for a global transition to a more sustainable and equitable future.

China and the United States show a minimum level of development of green hydrogen technology in comparison to Europe and the RoW, in view of the scientific results obtained in this study and in view of the IAE forecast in terms of installed electrolyzer power in the years 2023 and 2030. Europe and the RoW have the greatest citation impact of their research, in addition to being the ones with the most electrolyzer capacity in the year 2023 according to the IAE estimate [39], something that is estimated to remain the same in the year 2030.

Regarding the analysis of the most used electrolyzer technologies, the results obtained in this study show how the ALK and PEM electrolyzers are the ones that spark the greatest interest in the scientific community, with a minority being interested in the SOECs. Although ALK electrolyzers are the most widely used and studied by the scientific community, PEM electrolyzers are the most economically competitive and sustainable in terms of low greenhouse gas emissions.

Although green hydrogen has the potential to drastically transform different areas and contribute to a greener and more sustainable future, the results of this study show that research on this topic still has a long way to go. This is evidenced by the existence of approximately 300 research papers from 1993 to the present day, which is an average of only 10 results per year. Among the most used keywords, there are seven that are repeated in both periods: hydrogen, hydrogen production, hydrogen storage, solar energy, solar power generation, electrolysis, and fossil fuels. Based on the results, these keywords maintained their percentage of occurrence in the last period of 2011–2023, based on the number of research results obtained, but they managed to clearly reinforce their link and, therefore, increase the number of occasions on which they appeared together, in view of the substantial increase that the total link strength parameter has experienced.

In addition, throughout these papers, the keyword analysis shows that the words with the highest incidence are of a generic nature, without going into detail on relevant aspects of the technology. There is a clear need to develop more common guidelines and standards and to conduct more case studies.

Author Contributions: Conceptualization and methodology, P.F.-A. and D.V.; validation, P.F.-A., Á.A.-S., G.L. and D.V.; formal analysis, P.F.-A.; investigation, P.F.-A. and D.V.; writing—original draft preparation, P.F.-A., Á.A.-S., G.L. and D.V.; writing—review and editing, P.F.-A., Á.A.-S., G.L. and D.V.; supervision, P.F.-A., Á.A.-S., G.L. and D.V. All authors have read and agreed to the published version of the manuscript.

Funding: The authors wish to acknowledge the financial support provided by the following Spanish Institutions: Diputación de Ávila (Spain) for the project 2020–2024 PT 2022_002, in the framework of CTC, Innovation and Entrepreneurship of the Territorial Development Programme of Ávila and its Surroundings.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Acronyms and Nomenclatures	Description
ALK	Alkaline electrolyzer
CSP	Concentrated solar power
GHG	Greenhouse gas emissions
IEA	International Energy Agency
PEM	Proton exchange membrane electrolyzer
RoW	Rest of the world
SOEC	Solid oxide electrolytic cell

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