iSES Report

Innovation in Sustainable Energy Solutions

RENEWABLE HYDROGEN

FIRST EDITION

Adicionar:

Year 01 - Nº 01
March 2022

- Background and motivation
- Renewable Hydrogen
- Methodology
- Overview of global scientific production on renewable hydrogen
- Overview of global patent production on renewable hydrogen
- Overview of renewable hydrogen projects

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Innovation in Sustainable Energy Solutions – ISES Report

First edition – Renewable Hydrogen

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Report on Innovation in Sustainable Energy Solutions - ISES Report

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1. Background and motivation

Climate change has been a topic of discussion for almost 30 years, since Rio 92, one of the first major international meetings on climate. Over this period, the urgency of the scientific community's warnings has only grown . Today there is consensus that the continents are on average 1.6 °C warmer and that human activity has already caused irreversible damage to the planet (IPCC, 2021).

Given this scenario, several countries have sought cleaner alternatives, especially for the energy sector, as it is one of the main emitters of greenhouse gases. The use of hydrogen seems promising to contribute to the transition to a low-carbon economy. However, this use is contingent on developing different methods of hydrogen production than the ones currently employed.

Hydrogen supply today is mainly based on the steam reforming of natural gas and the partial oxidation of fossil fuels such as coal (IEA, 2019). However, hydrogen can be produced from other more sustainable processes, such as water electrolysis using electricity from renewable energy sources, and the reforming of biomass and other products such as ethanol and glycerol.

Figure 1 shows a schematic representation of technological routes to obtain hydrogen. It was published by EPE and referenced the Energy Hydrogen in Brazil report. Subsidies for competitiveness policies, 2010-2025, critical and sensitive technologies in priority sectors of CGEE (EPE, 2021; CGEE 2010. *Hidrogênio energético no Brasil*. *Subsídios para políticas de competitividade, 2010-2025*, *tecnologias críticas e sensíveis em setores prioritários*). Figure 1 also presents different opportunities for the use of hydrogen.

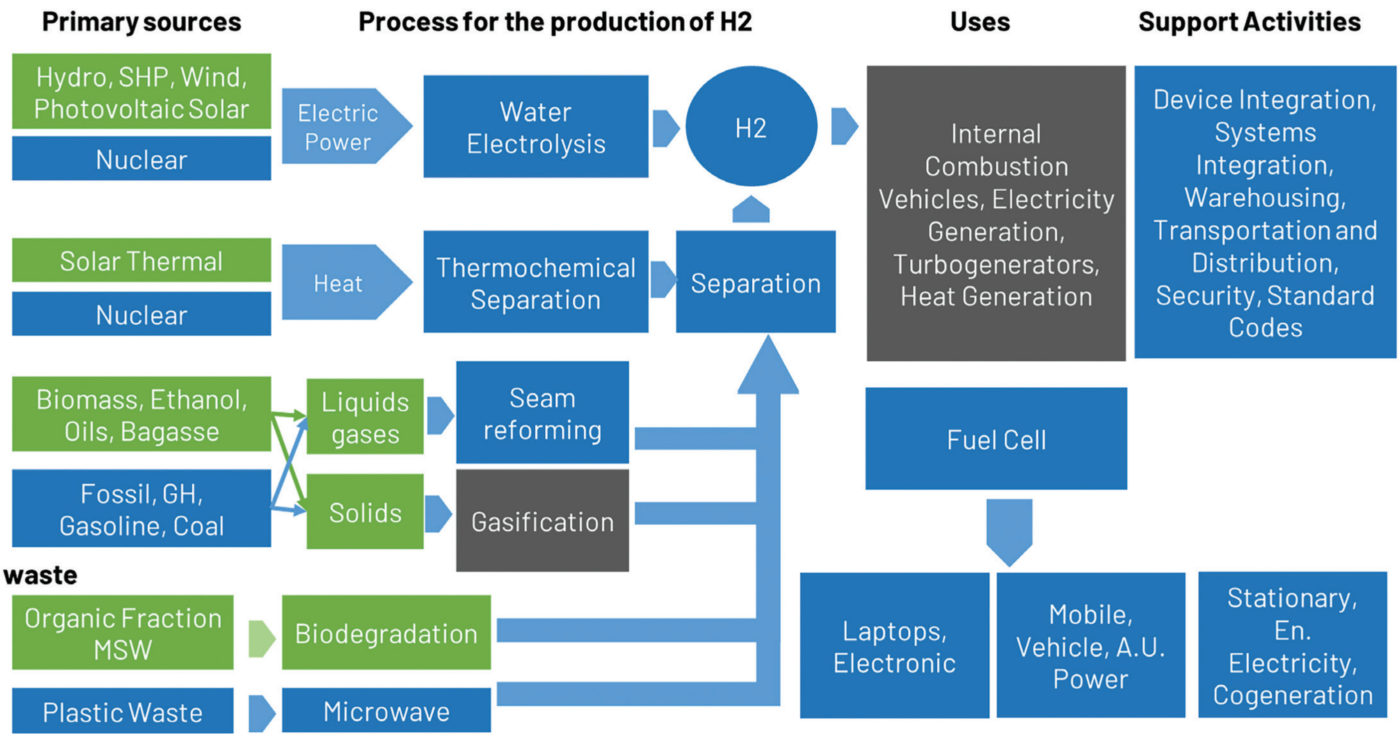

Figure 1: Representation of the technological methods to obtain hydrogen. Source: EPE (2021)

[1] As an effect of anthropogenic emissions, the planet has warmed by an average of 1.1°C, but with warming in the continents of 1.6°C (IPCC, 2021)

Currently, hydrogen has been used mainly for the production of ammonia and in oil refineries (IEA, 2019). However, expectations related to the future use of a renewable hydrogen are mainly about its energy use. *The European Green Deal*, for example, which seeks carbon neutrality in Europe by 2050, points out that the share of hydrogen in Europe's energy matrix is expected to grow from the current less than 2% to 13-14% by 2050 (European Commission, 2020).

In addition to energy use, hydrogen also has the potential to drive a low-carbon economy through more sustainable products, as in the case of the steel industry. The study Challenges and opportunities for Brazil with green hydrogen (*Desafios e oportunidades para o Brasil com o hidrogênio verde*) published by the E+ institute in partnership with the Heinrich Böll Stiftung Foundation showed the use of hydrogen in the steel industry as one of the three main opportunities for hydrogen in the country.

The great expectation regarding hydrogen is, in fact, related to a large set of opportunities. First, hydrogen is a light, high-calorific gas, which allows, for example, clean combustion with high energy content for a small mass of product. Hydrogen can also function as a vector for renewable energy storage, facilitating the connection between production sites and more distant consumer centers. Hydrogen is also considered a pathway for electrification in the transportation sector, primarily through fuel cell technologies.

The challenges, however, are still considerable. Development is still needed in the diffusion of new technologies and in the infrastructure for hydrogen production, storage, transport, and distribution. In particular, the storage challenge is noteworthy because hydrogen is extremely light, which imposes significant constraints on the process of increasing its energy density. Such processes carry risks, as they require high pressures for storage in the gaseous state or cryogenics for storage in the liquid state. Here, we may note the absence of an adequate institutional, legal and regulatory framework for the energy use of hydrogen.

In spite of the efforts still to be made to develop a hydrogen-based economy, several countries have launched their national strategies and plans, such as Germany, the United Kingdom, South Africa, the United States, Canada, South Korea, and Chile. Brazil also started the development of the National Hydrogen Program (PNH) with the document *Bases for the Consolidation of the Brazilian Hydrogen Strategy* (EPE, 2021) and the Guidelines for the PNH (MME, 2021) as the main milestones. International institutions have also made recent efforts to promote the hydrogen economy, such as the International Energy Agency (IEA, 2019), International Renewable Energy Agency (IRENA, 2019), and the Energy Transitions Commission (Energy Transitions Commission, 2021).

We can also see the growing interest in hydrogen from renewable sources by the volume of searches on Google for the term "*green hydrogen*" as hydrogen from renewable sources has been commonly called . The graph in Figure 2 shows a slight increase in searches for the term "*hydrogen production*", but a significant increase in searches for the term that is a specific, clean, and sustainable type of hydrogen production.

[2] This Report uses the term **renewable hydrogen** to refer to hydrogen from renewable sources. However, the term "green hydrogen" - mainly in English - has been the most widely used worldwide. Section 2 of this The report presents the different terms that have been used and justifies the choice of the term **renewable hydrogen**.

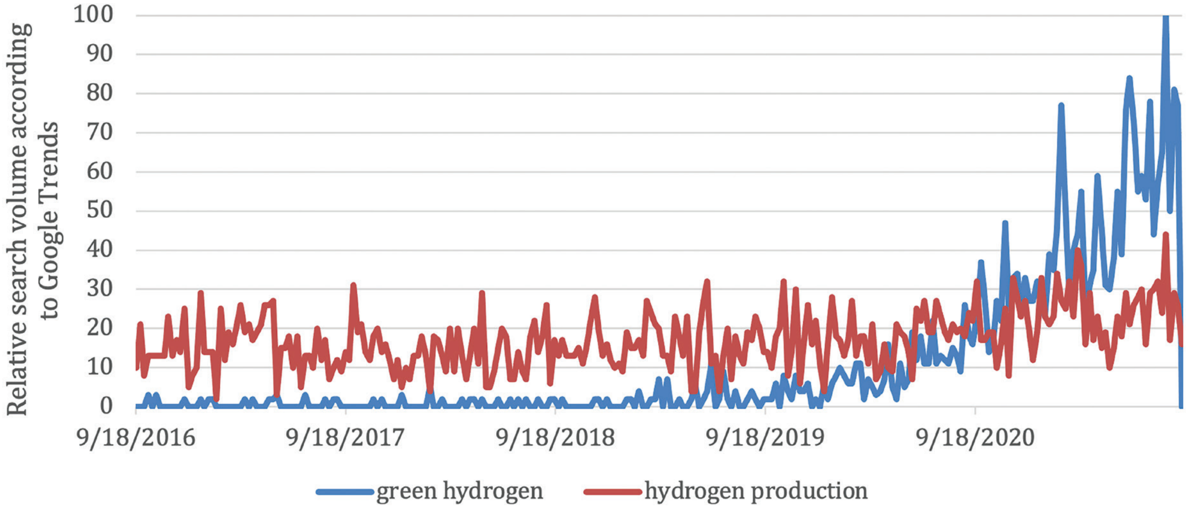

Figure 2: Relative search volume according to Google Trends

In this context, it is important to provide decision-makers with quality inputs to understand the global movements related to renewable hydrogen. To add to existing contributions, the first edition of the Innovation in Sustainable Energy Solutions Report (ISES Report) presents an overview of scientific papers, patents, and commercial projects on renewable hydrogen (RH2) worldwide.

In addition to this introduction, this Report contains six other sections. Section 2 discusses the different terms and definitions for renewable hydrogen. Section 3 presents the main methodological aspects of the ISES Report. Sections 4, 5, and 6 present the results of the surveys on scientific papers, patents, and commercial projects in renewable hydrogen, respectively. Finally, section 7 presents the final considerations.

2. Renewable hydrogen

To meet the expectations of a hydrogen-based economy, it is paramount to consider sustainable ways of obtaining hydrogen. Over the past five years, a color-based classification has emerged containing the various types of hydrogen based on their production process. In most cases, hydrogen is divided into gray, blue, and green. Grey is hydrogen from fossil sources, blue is hydrogen produced from fossil sources but with carbon capture, and green refers to hydrogen produced from the electrolysis of water using renewable energy sources (ICLEI, 2021; Hydrogen Council, 2021).

However, this classification does not include or specify other production processes or methodological aspects of the ISES Report. The International Energy Agency, for example, divides the production of hydrogen from fossil sources into three colors: black, from coal, gray, from natural gas, and brown, from lignite (IEA, 2021a). The EPE includes moss hydrogen to refer to hydrogen from biomass or biofuels, with or without carbon capture, through catalytic reforming, gasification, or anaerobic biodigestion (EPE, 2021). It is also worth mentioning the existence of turquoise, generated from methane pyrolysis; red (which can also be pink or purple), generated from electrolysis using nuclear energy; and white, being natural or geological hydrogen (Box 1).

Box 1 - Natural Hydrogen

Source: *Miranda, Paulo Emílio. Hydrogen Energy: Sustainable and Perennial.* ***In: Science and Engineering of Hydrogen-Based Energy Technologies****. Academic Press. Elsevier. 2019 (1-35)*

In spite of all the well-known or the new and sophisticated technologies for hydrogen production and the belief kept for so long that these are the possible ways to make hydrogen fuel viable for use on earth, exploration of natural hydrogen, not once considered possible, is beginning to become reality. There is no doubt that hydrogen is the most abundant element in the Universe. On earth it was thought to exist only bound to compounds, into any hydrocarbons and water, being one of the constituents of all flora and fauna. The gas hydrogen was not considered to be available on earth, either mixed with other gases or in high proportion, almost pure, because it is composed of such a reactive chemical element. However, recent evidence proves the contrary. Fig. 1.12 shows a circular geological structure on the earth's surface in Brazil where measurements are made to detect continuous outgassing of natural hydrogen [54]. These circular, sometimes elliptical, structures that may possess a few meters or kilometers of diameter are zones of deformation of the soil, resulting from basement faults, bounded by rounded depressions of a few meters, presenting inside a flat bottom.

Figure 3: Geological structure composed of a circular depression on a craton zone formation in Brazil where hydrogen gas is detected flowing out. Reproduced from: Moretti et al. (2018).

They have also been found elsewhere, such as in North America, the Sultanate of Oman, Philippines, Mali, Turkey, New Caledonia, and Russia (Moretti et al., 2018; Deville & Prinzhofer, 2016; Larin et al., 2015). The following are considered as characteristics and mechanisms related to natural hydrogen existence on earth (Deville & Prinzhofer, 2016):

1. Natural hydrogen outgassing is now understood to appear in craton formation regions that are rock formations on the earth's continental crust that have remained stable for a period of time as extended as 500 million years.

2. Hydrogen is found at the earth's free surface and in fairly shallow depths of up to about 500 m (Larin et al., 2015);
3. Natural molecular hydrogen also occurs in ophiolitic2 formations, eventually associated with nitrogen and abiotic methane, whose generation is not linked with organic matter thermal cracking but by reduction of any source of carbon. That is, there is no organic matter accumulation associated with the sites of occurrence, situation in which hydrocarbons would rather be produced.
4. The effect of serpentinization[3] in peridotite, a very dense, coarse-grained, olivine-rich [$(Mg^{2+}, Fe^{2+})_2 SiO_4$] ultramafic rock, which is a silicate mineral rich in magnesium (forsterite end-member[4]) and iron (fayalite endmember), is twofold (Larin et al. 2015):
   a. The hydration of the forsterite end-member of olivine (Mg2SiO4) produces much hydroxide ion, such as in Eq. (1.3), to make it an ultrabasic rock:

      $$2Mg_2 SiO_4 + 3H_2 O \rightarrow Mg_3 Si_2 O_5 (OH)_4 + Mg^2 + +_2 OH^-$$

      Or even, in a simplified way:
      Fosterite + water → serpentine + magnesium + hydroxide ion
   b. Since Fe+2 is by far the most important electron donor in ultrabasic rocks, hydration of the iron end-member (fayalite) of olivine minerals induces the formation of Fe+3 minerals such as magnetite, leading to the formation of hydrogen as depicted in the equation below:

      $$3Fe_2 SiO_4 + 2H_2 O \rightarrow 2Fe_3 O_4 + 3SiO_2 + 2H_2$$

      Or even, in a simplified way:
      Fayalite + water → magnetite + silica + hydrogen

The existence of aquifers under the earth's surface in geologically stable craton formation regions may represent a mechanism of continuously promoting the formation of natural hydrogen, as far as ferrous iron is present in their surrounding (as olivine, or as any other mineral containing ferrous iron being able to decompose and liberate soluble Fe2þ in water). This may eventually be consistent with the amazing possibility of replenishing natural hydrogen wells with new-formed gas.

The first hydrogen wells actually producing natural hydrogen in the world are being explored in Bourakebougou, in Mali, Africa. It was the search for water in that region that unveiled the presence of gaseous occurrence composed of 98% of pure natural hydrogen 1% of nitrogen and 1% of methane that is explored and used locally for electricity generation [54]. The natural hydrogen wells are a little over 100 meters below the earth's surface in that region, confirming that this energy resource may be available in shallow wells for which the technological setup for exploration becomes simpler and cheaper. This may result on the extraordinary possibility of harvesting natural hydrogen at a cost smaller than that of hydrogen produced by any of the methods known to date, from the conventional natural gas steam reforming and the well-developed water electrolysis to the innovative technologies hitherto discussed.

Because it has been herein showed that the first world's natural hydrogen wells are under production in Mali, on the northeast of Africa and because natural hydrogen occurrence has also been proved to exist in the northeast of South America, in Brazil (Figure 3), considering that it is known that the South American

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[3] Serpentine rocks are formed as a result of hydration processes, such as serpentinization, when the spreading tectonic plates in the earth's crust lift them up from the ocean and they are chemically altered by water or, alternatively, when a similar process is induced by the presence of the underlying aquifers that promote water movement.

[4] End-member is a mineral that is at the extreme end of a mineral series in terms of purity. Fayalite Fe2SiO4 and forsterite Mg2SiO4 are end-members of the olivine series (Mg,Fe)2SiO4.

Adicionar:
5 The final member is a mineral which is at the end of a series of minerals in terms of purity. Faialite Fe2SiO4 and forsterite Mg2SiO4 are final members of olivina's series (Mg, Fe) 2SiO4

and African continents once joined together, in old geological era, forming the Pangea supercontinent as depicted in Figure 4, and that they may share similar geological structures, an analysis was made of the potentiality of discovering simultaneous occurrence of craton formation regions on the top of the underlying aquifers in these continents, which would bring the possibility to identify other possible regions where natural hydrogen wells would likely be found. The resulting analysis is shown in Fig. 1.14. It is absolutely amazing to verify that there are several coincident occurrences of craton rock formations onto the underlying aquifers both in South America and in Africa, Figure 4. The formation verified in the Amazon region calls attention for its enormous extension.

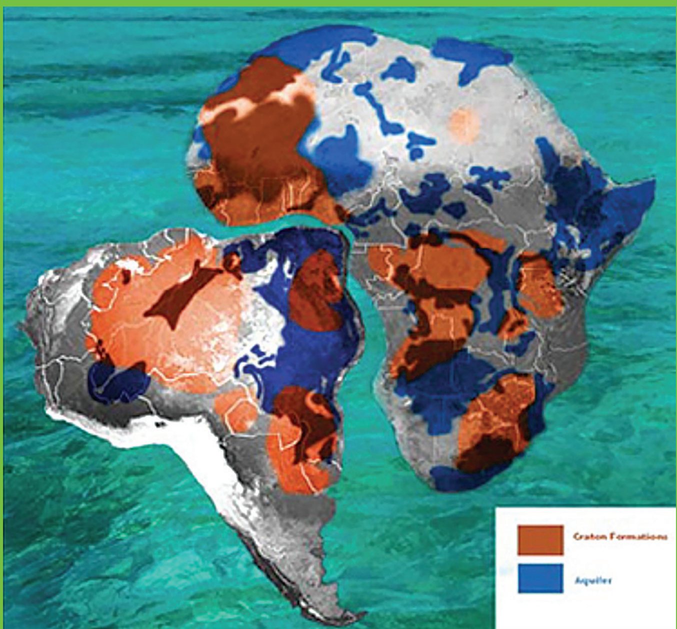

Figure 4: South American and African continents joining together in old geological era that once formed the Pangea supercontinent. Regions where craton rock formations are found on the top of the underlying aquifers in South America and Africa are indicated with different color contrasts.

In addition, taking into account that natural hydrogen-rich gaseous formations were found on the paleo ocean floor in New Caledonia (ophiolite), it is conceivable to admit that in the vast intercontinental oceanic extensions, there might exist several sites where natural hydrogen is likely to be found and explored, the feasibility of which will be very much dependent on the depth and local conditions but will benefit from the experience already accumulated with the exploration of hydrocarbons in the ocean. It is also important to remark that an eventual future exploration of subsea natural hydrogen will never submit such sites to the danger of extraordinary environmental disasters such as the ones already occurred with the exploration of hydrocarbons, oil and natural gas, simply because hydrogen would be partially absorbed by water and partially vented to be consumed in open air, thereby producing water.

Even though the term "green hydrogen" may be used to refer to more than just hydrogen produced from water electrolysis using renewable energy sources, color nomenclature (brown, blue, and green hydrogen) is still disputed among scholars. For this reason, this report avoided this nomenclature, despite its didactic aspects.

The focus of this report is to make contributions on **renewable hydrogen**, i.e., hydrogen produced from renewable sources, regardless of the type of process (electrolysis, thermochemical or biochemical) and the possibility of carbon capture. A definition of renewable hydrogen was proposed by Martinez-Burgos *et al.* (2021). According to the authors:

"Renewable hydrogen can be obtained using water as a raw material through processes such as electrolysis, thermolysis, and photolysis; employing different types of waste as substrates for biophotolysis, dark fermentation and photo-fermentation; through the reformulation of bio-methane; or by thermochemical processing (Pyrolysis, Gasification, Combustion, Liquefaction) using different types of biomass"

Figure 5 presents the classification used by Martinez-Burgos et al. (2021).

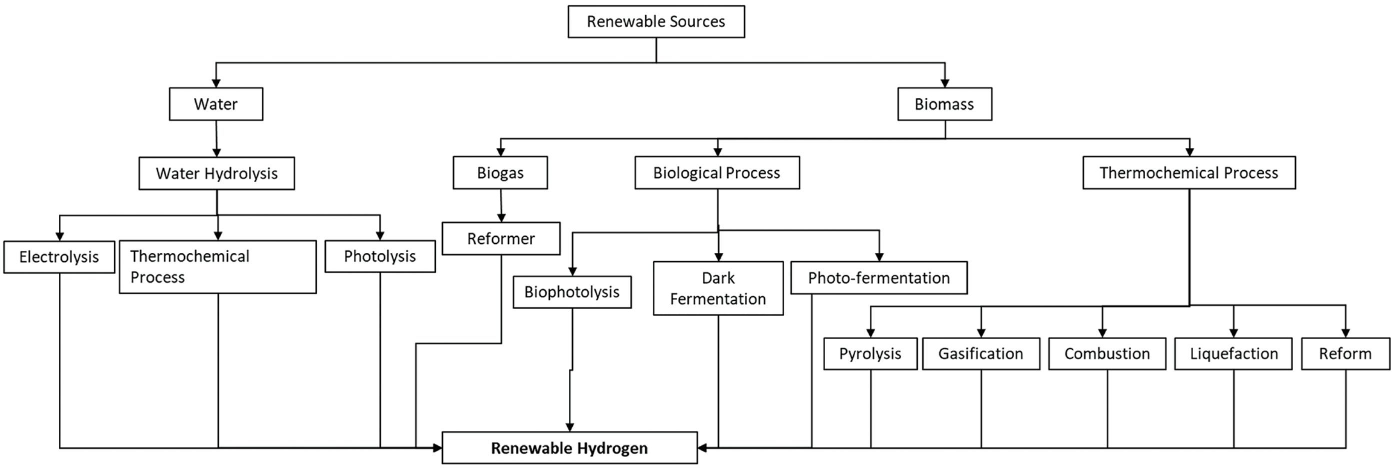

Figure 5: Classification of hydrogen production routes from renewable sources. Source: Translated from Martinez-Burgos et al. (2021).

The decision to use the term **renewable** and broaden the scope beyond electrolysis hydrogen, or green hydrogen, was made for three main reasons. First, to emphasize that hydrogen can be "green" even if it is produced from processes other than water electrolysis from electricity generated from renewable sources. This emphasis is important to avoid missed opportunities. For example, although some biological processes currently have low efficiency for dedicated production, they can generate hydrogen as a co-product in processes that aim to reduce pollution, stimulate the reuse of materials and take advantage of waste and effluents (Sarangi & Nanda, 2020).

Secondly, broadening the scope of analysis means looking at processes that use raw materials that are abundant in Brazil, such as ethanol and sugarcane waste, and glycerol as a co-product of biodiesel production. Third, analyzing hydrogen from renewable sources challenges us to consider an economy that is increasingly less dependent on fossil resources, even if using processes with smaller carbon footprints, such as blue hydrogen.

The next sections present the methodological aspects and the global outlook for renewable hydrogen in terms of scientific production, patents, and projects.

3. Methodology

AThe first edition of the ISES Report aims to provide an overview of scientific papers, patents, and commercial projects on renewable hydrogen worldwide. For this purpose, the ISES Report Renewable Hydrogen Working Group (ISES RH2 WG) was set up with hydrogen experts. The ISES RH2 WG mainly contributed in: (a) raising guiding questions that shaped this Report; (b) validating the data search methodologies (papers, patents, and projects), suggesting the most relevant types of analysis; and c) checking the results found.

The ISES RH2 WG was formed by eight experts from the following institutions: Unicamp (1), UFRJ (2), INT (2), EPE (2), and E+ Institute (1). There were five working group meetings and five individual meetings (representatives of the institution + CGEE team), in addition to suggestions and revisions sent by email. Other institutions also contributed to the Report, such as the International Energy Agency (IEA), mainly with guiding questions and information on commercial renewable hydrogen projects (IEA, 2021).

In addition to the ISES RH2 WG and individual consultations, CGEE organized, on 11/23/2021, **the International Dialogue Panel 2021 - The Era of Renewable Hydrogen**. The goal was to find out what actions are being taken in the world to deal with the opportunities and challenges of renewable hydrogen, according to young international researchers. The event had 85 participants among lecturers, organizers, collaborators, and the audience. After the event, we produced the executive summary **International Dialogue Panel - The Era of Renewable Hydrogen (CGEE, 2021)**. Both the event and the executive summary served as sources of information for discussions on the contextualization of RH2 and for the analysis of panoramas of scientific papers, patents, and commercial projects.

During all analyses - scientific papers, patents, and projects - the main challenge was to define the scope of the search. The topic “hydrogen” involves several aspects, such as production, storage, transportation, and use. For this report, which focuses on **renewable hydrogen**, the search criteria focused mainly on the production stage, which characterizes the renewability of hydrogen, depending on the raw material used.

For the three analyses produced, we sought to form a sample that was representative of the hydrogen universe. Also, we did not intend to exhaustively capture and analyze all data from papers, patents, or projects on the subject. The specific methodologies for each analysis are discussed in sections 4, 5, and 6.

4. Overview of global scientific production on renewable hydrogen

This section aims to present the panorama of scientific papers on renewable hydrogen (RH2). Initially, the methodology used to collect RH2-related data will be presented, followed by the results of bibliometric analysis.

To survey scientific papers, a methodology was developed to capture a representative sample of papers on RH2 (Figure 6). First, review papers that contained the term ***green hydrogen*** were collected. These papers were analyzed to identify the types of technologies and terms involved with the topic. Thus, a set of 24 terms associated with RH2 was defined and reviewed by the ISES RH2 WG. Such terms were synonyms and similar to ***green hydrogen***, such as ***renewable hydrogen, sustainable hydrogen,*** and ***biohydrogen***. This search raised 13,165 papers and formed the **central network** of scientific papers.

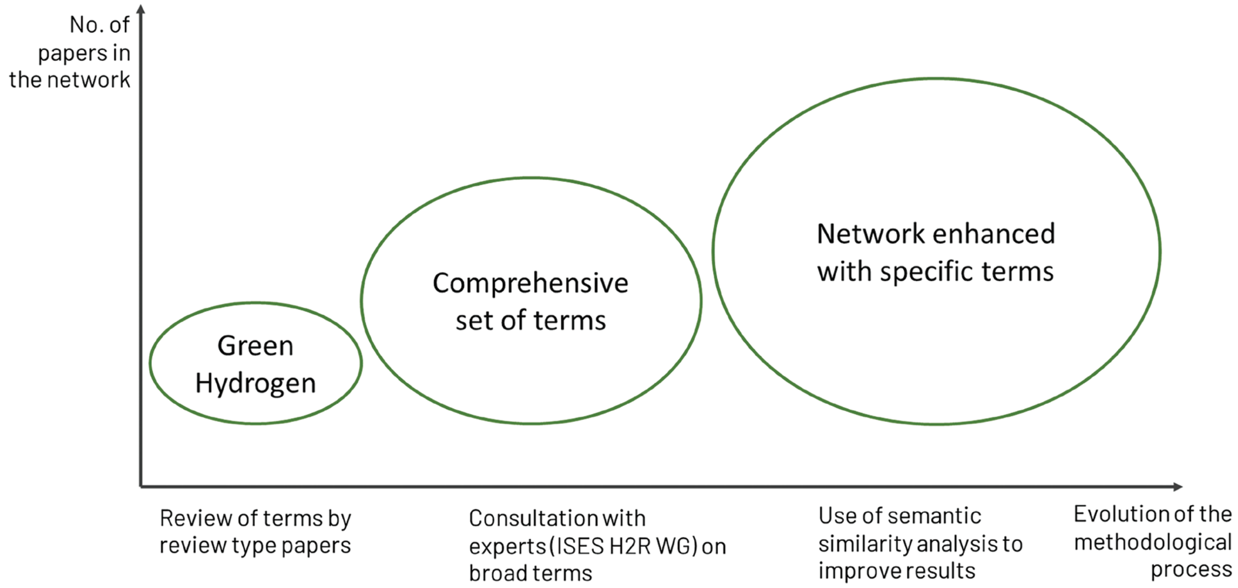

Figure 6: Methodology for the survey of scientific papers on renewable hydrogen

Aiming to improve the network, 12 sets of papers were collected based on 12 terms related to renewable hydrogen production processes. These terms were based on the paper by Martinez-Burgos et al. (2021) presented in section 2 and the ISES RH2 WG review. Each of these sets was added to the central network, and the semantic similarities of titles, abstracts, and keywords were calculated (Figure 7) using CGEE's own software: Insight Net. Papers from the sets with a high degree of semantic similarity with the central network - or the **first neighbors** - were added to the central network. After conducting this process with the 12 sets, the final network reached a total of 16,620 scientific papers. It is important to highlight that the Web of Science (WoS) database was used. The analysis considered the entire time series available.

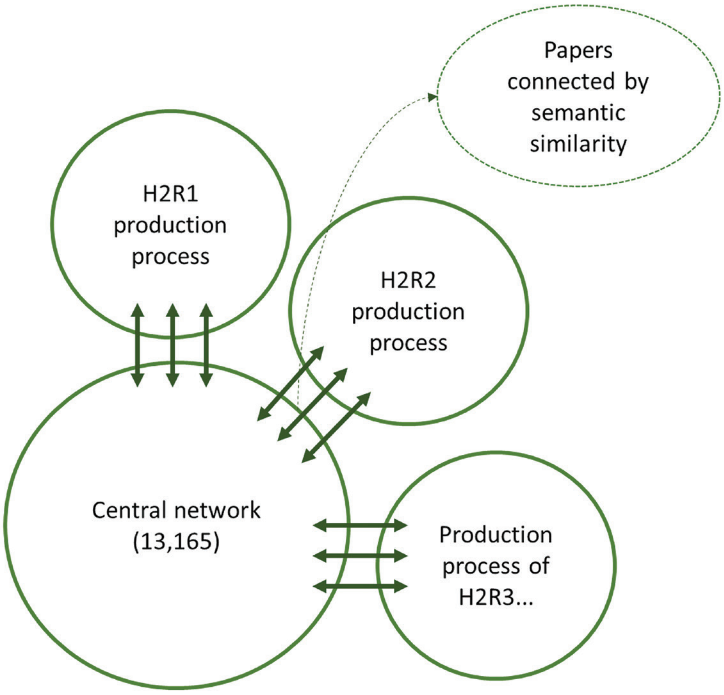

Figure 7: Enhancement process by semantic similarity of the scientific paper network

4.1. Overview of the renewable hydrogen network

The final network with 16,620 papers connected by semantic similarity can be seen in Figure 8. The closest nodes indicate papers with similar subjects, and the colors indicate modularity classes calculated by the Insight Net software to identify thematic clusters.

Figure 9 shows the word cloud of the complete network, and Table 1 shows the frequency of occurrence of the first 20 keywords. After the word **hydrogen**, the most cited words are **biohydrogen** and **biomass**, which is interesting to note as these point to alternative processes and raw materials. "Biohydrogen" can refer to either hydrogen produced from biological processes or hydrogen produced from biomass[5]. In both cases, these words indicate ways of obtaining RH2 by methods other than water electrolysis

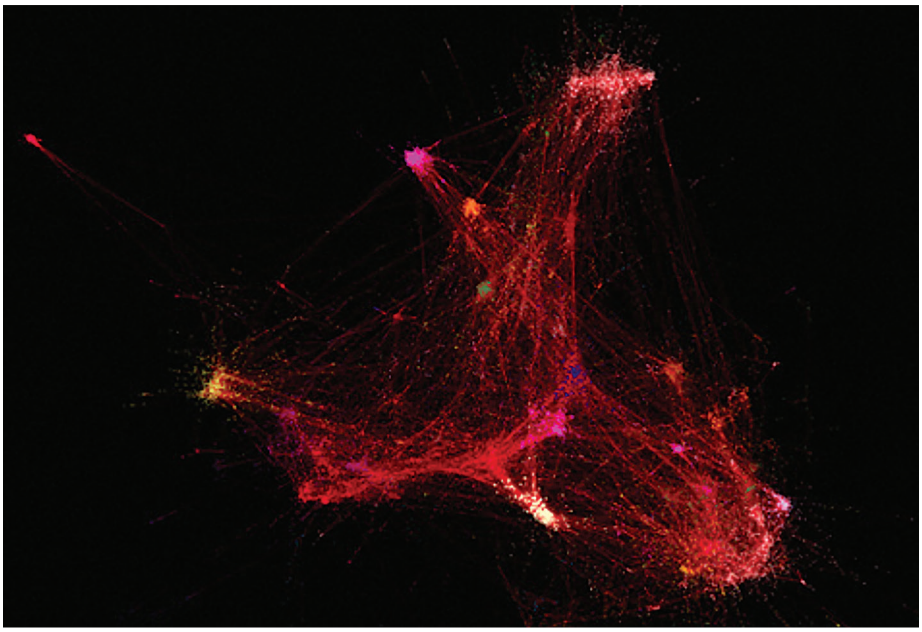

Figure 8: Semantic similarity network of scientific papers in RH2.

[5] In this Report, biohydrogen will be treated as that produced by biological methods.

 Esse é o número 6

- as has been discussed regarding **green hydrogen**. Other words also indicate this fact, such as **dark fermentation**, **wastewater**, and **food waste** - process and possible raw materials for biohydrogen, respectively.

The process of **electrolysis** of water by electricity produced from renewable energy can also be detected through the words: **electrolysis**, **water**, and **renewable energy**.

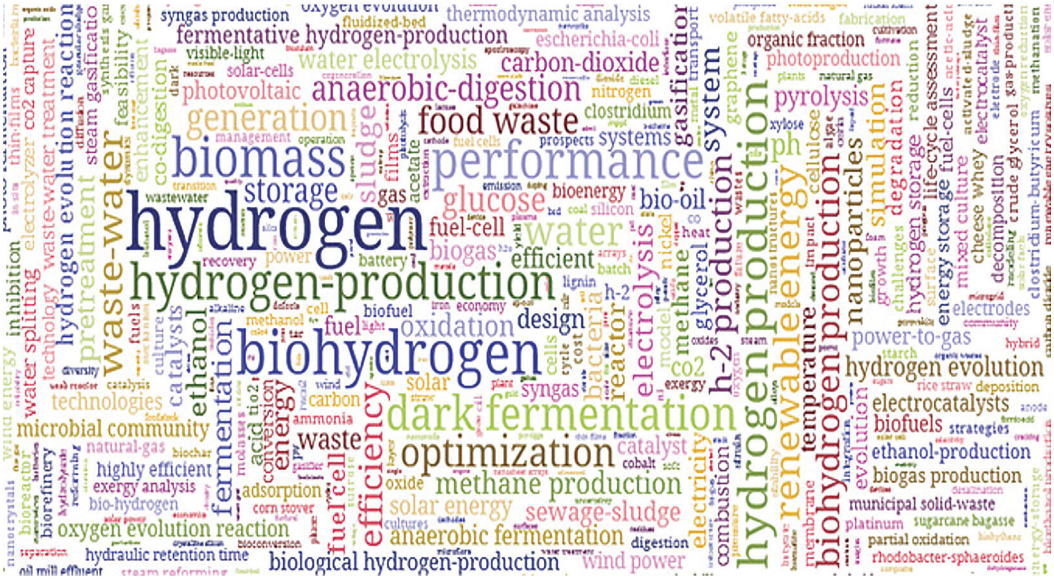

Figure 9: Word cloud of the RH2 network

Table 1: 20 most cited keywords in the scientific papers network

	Word	Frequency		Word	Frequency
1	hydrogen	2984	11	renewable energy	830
2	biohydrogen	1749	12	generation	665
3	biomass	1335	13	food waste	662
4	performance	1303	14	biohydrogen production	605
5	hydrogen-production	1207	15	efficiency	599
6	hydrogen production	1135	16	glucose	594
7	dark fermentation	1087	17	h-2 production	566
8	water	864	18	anaerobic-digestion	557
9	optimization	860	19	electrolysis	516
10	waste-water	832	20	sludge	511

Figure 10 presents the evolution of the number of papers of the network over the years. The number of papers has been growing since 2004. The lower number of papers in the year 2021 is due to the fact that the initial papers in the central network were listed in August 2021. It seems reasonable to assume that the year 2021 will maintain the growth trend. Aiming at a deeper characterization of the network, the next section will present the analysis of 6 thematic clusters.

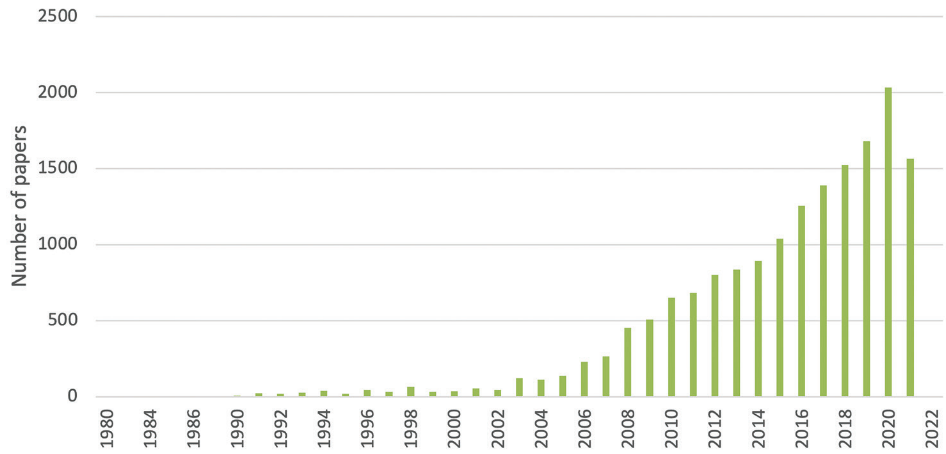

Figure 10: Evolution of the number of papers over time

4.2. Characterization of the network

Figure 11 presents the semantic similarity network with the 6 clusters highlighted. For each cluster, we will present a brief description, its respective word cloud, and a list of the five countries that published the most in it.

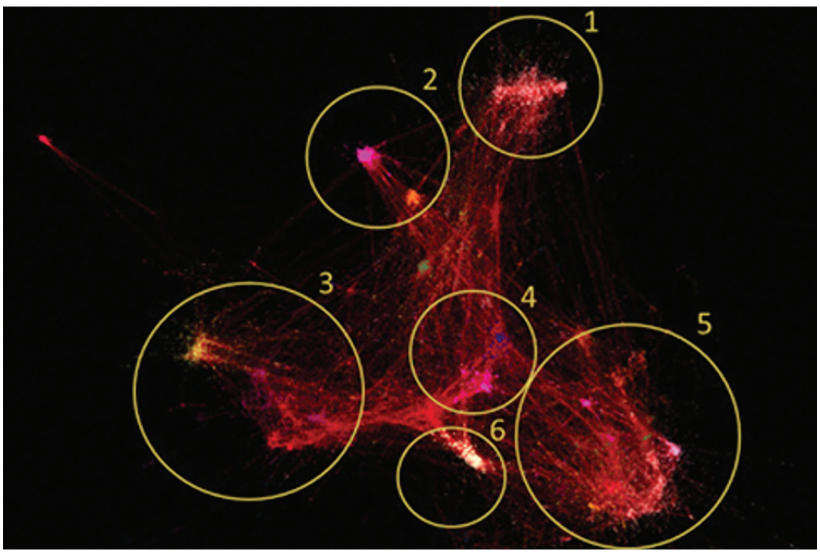

Figure 11: Semantic similarity network with the 6 clusters highlighted

4.2.1. Cluster 1: Hybrid renewable energy systems

Cluster 1 is found at the top of the network and has high concentration, indicating that the papers have quite similar topics among them. The word cloud and the five countries that published most in cluster 1 can be seen in Figure 12 and Figure 13, respectively.

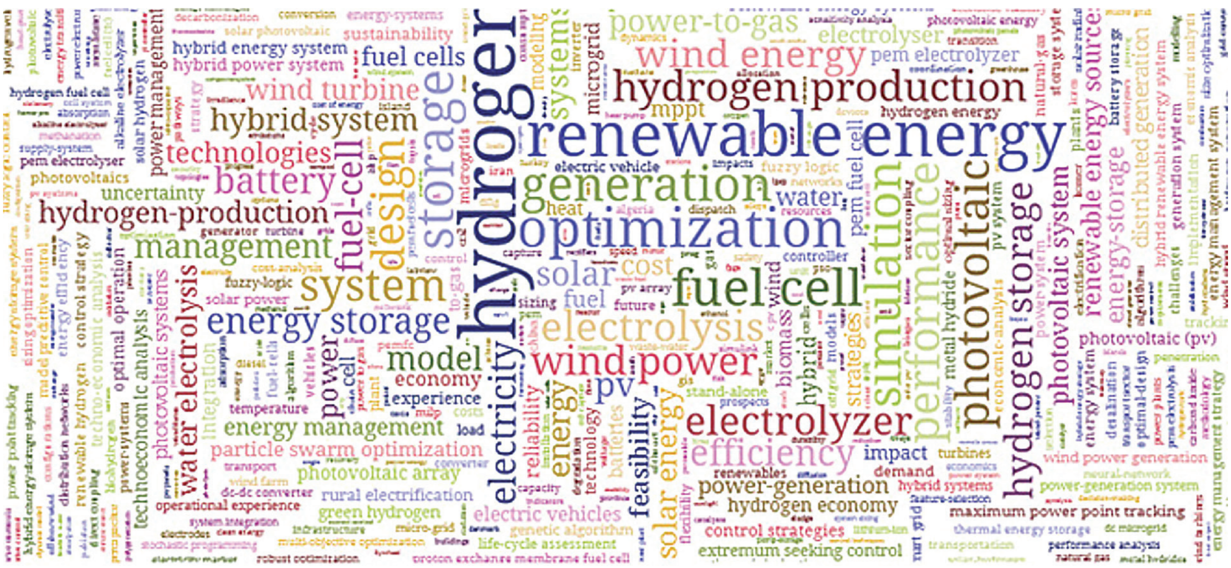

Figure 12: Word cloud of cluster 1

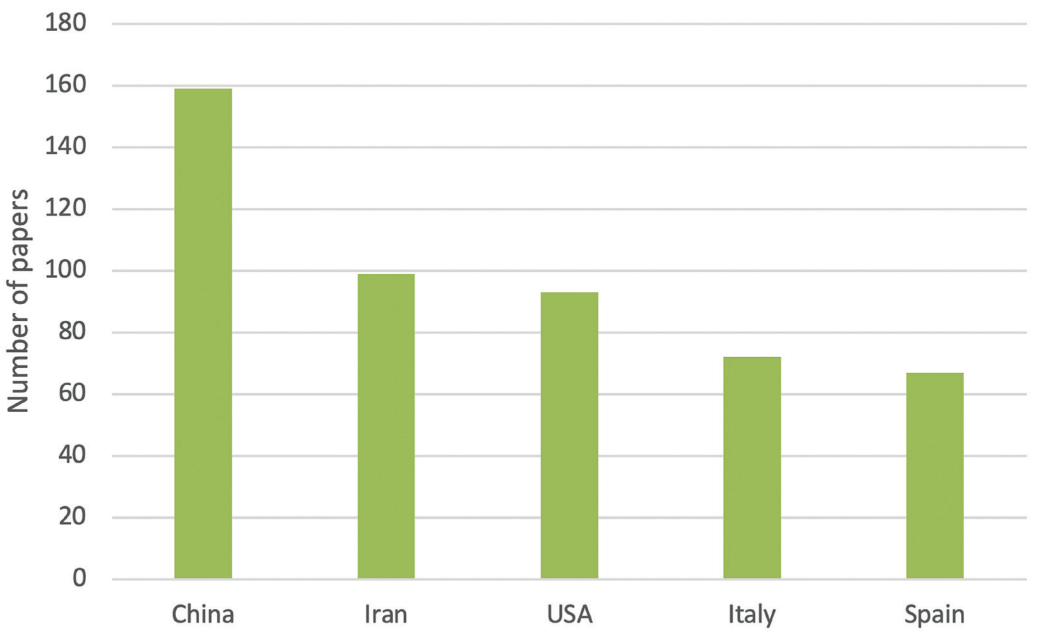

Figure 13: Five countries that published the most in cluster 1

Cluster 1 contained 1,720 articles covering different topics related to the production and use of renewable hydrogen, especially in a hybrid systems context. Several papers discuss the use of electrolyzers to store energy generated by intermittent sources such as wind and solar. Many of the papers discuss methods to optimize these hybrid renewable energy systems.

We can see in Figure 13 that China is the country that had the most publications in the cluster, followed by Iran and the United States.

4.2.2. Cluster 2: Renewable ammonia end dual-fuel systems

Cluster 2 is found at the top left of the network and can be divided into two sub-clusters, both extremely concentrated. The keyword cloud and the five countries that have published the most in cluster 2 can be seen in Figure 14 and Figure 15, respectively.

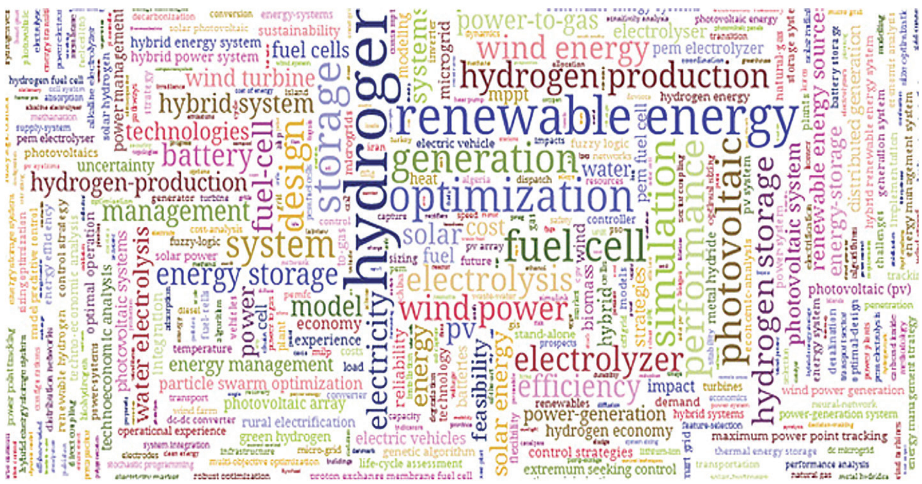

Figure 14: Word cloud of cluster 2

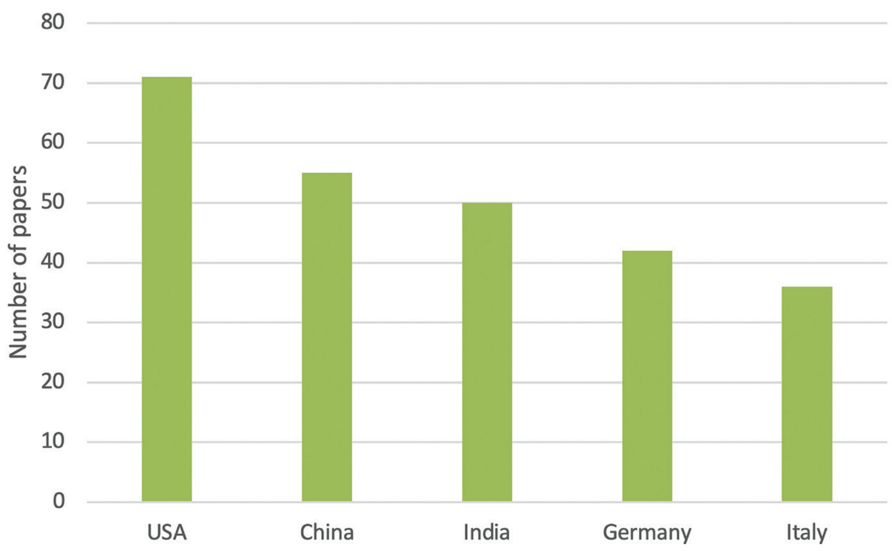

Figure 15: Five countries that published the most in cluster 2

Cluster 2 is smaller, containing 741 papers. In the innermost part of the network, cluster 2 presents a sub-cluster that deals mainly with the **production and use of renewable ammonia**. In the second sub-cluster - peripheral to the network - papers discuss different forms of analysis of the **combustion efficiency of hydrogen and ammonia** with a focus on **dual-fuel hydrogen/diesel systems**. The two sub-clusters are connected by papers dealing with the use of renewable ammonia in combustion engines. Figure 15 shows the United States as the country that published most in the cluster, followed by China, India, Germany, and Italy.

4.2.3. Hydrogen production by electrolysis of water

Cluster 3 is larger than the previous ones, with 2,479 papers spread across several sub-clusters located on the left side of the network. The word cloud and the five countries that published most in cluster 3 can be seen in Figure 16 and Figure 17, respectively.

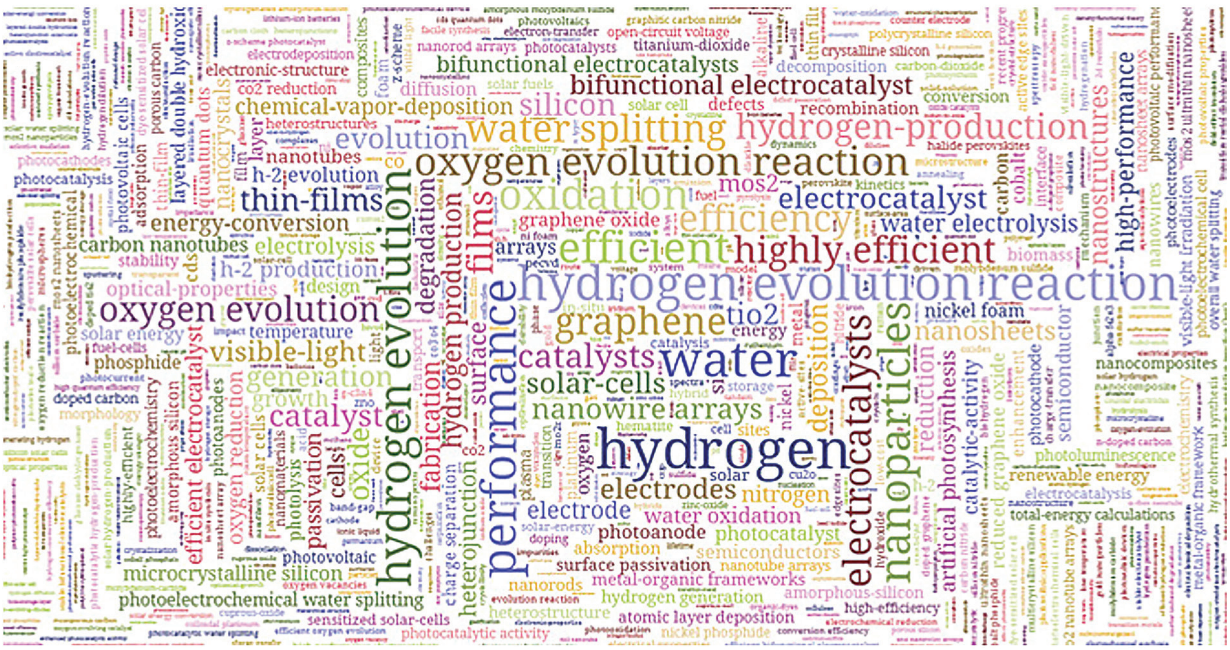

Figure 16: Word cloud of cluster 3

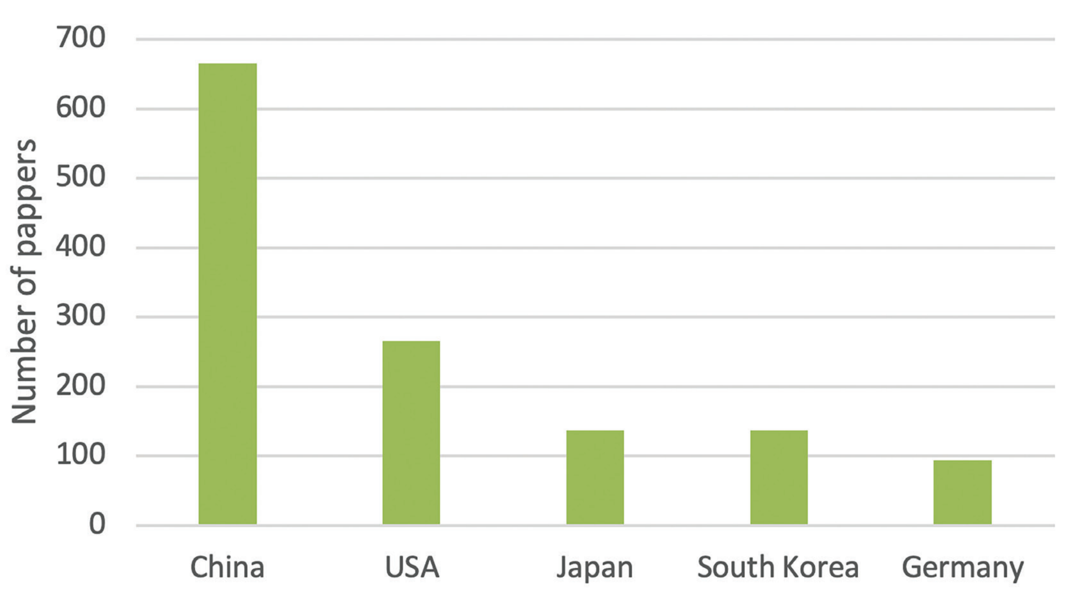

Figure 17: Five countries that published the most in cluster 3

Cluster 3 contains papers discussing water electrolysis processes. This can be seen by the keywords: hydrogen evolution reaction, oxygen evolution reaction, and water splitting which appear frequently in the cluster. Amongst the most frequent subjects, there are analyses on the production, use, and efficiency of catalysts and electrocatalysts to increase the efficiency of the electrolysis process. The sub-clusters are formed by different types of catalysts, production techniques, and efficiency analyses. China is the country with the largest number of papers in the cluster, followed by the United States, with less than half of the Chinese production.

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4.2.4. Cluster 4: Thermochemical processes for producing hydrogen from biomass

Cluster 4 is in the central part of the network with a total of 923 papers. The word cloud and the five countries that published the most in cluster 4 can be seen in Figure 18 and Figure 19, respectively.

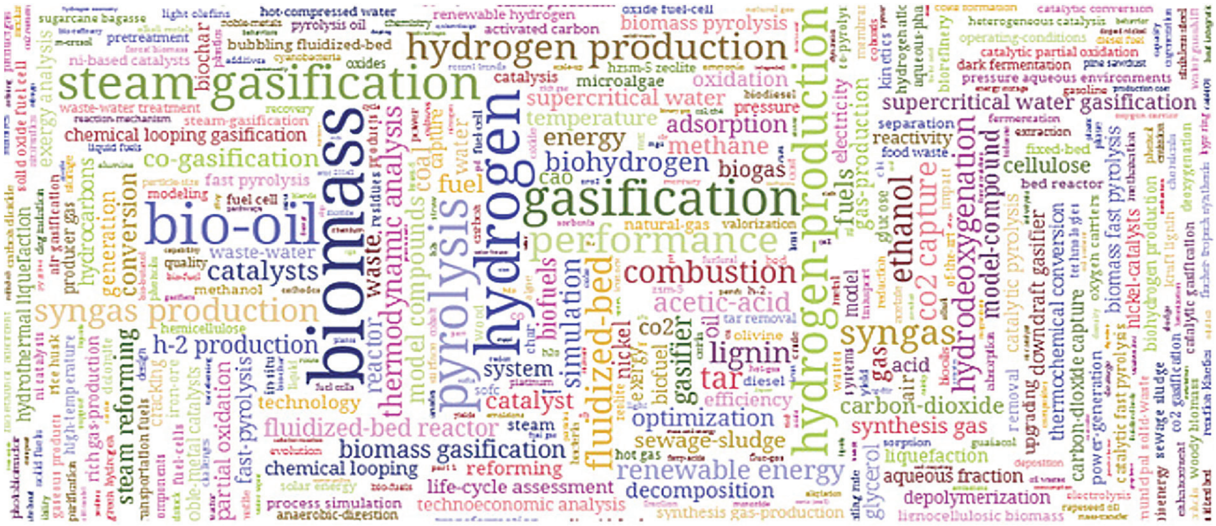

Figure 18: Word cloud of cluster 4

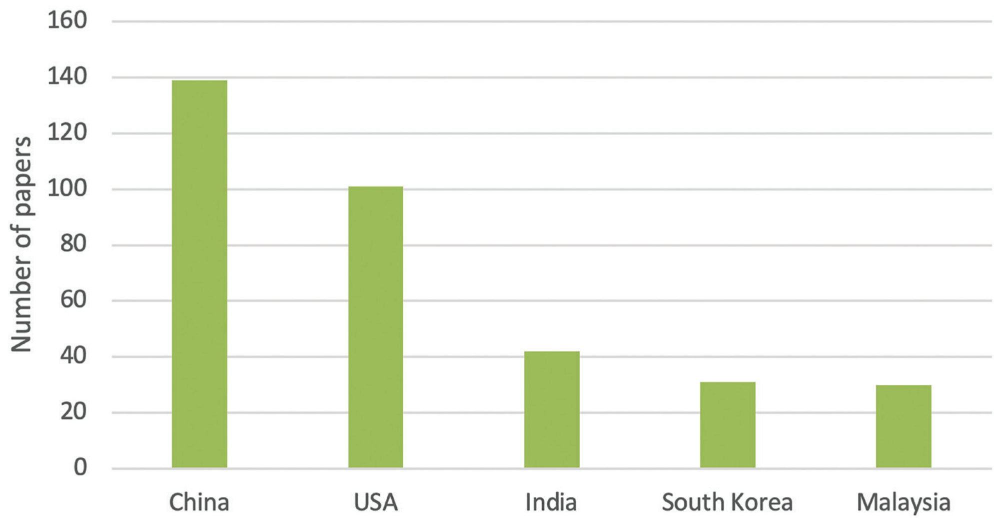

Figure 19: Five countries that published the most in cluster 4

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Cluster 4 addresses various processes for producing renewable hydrogen from biomass or biomass-derived products such as biogas and bio-oil. These processes are mainly thermochemical. The papers vary with respect to the type of raw material used, such as biogas, biomass, and bio-oil, and the types of processes studied, such as gasification, pyrolysis, and reforming. The main countries that published in cluster 4 were China and the USA.

4.2.5. Cluster 5: Biohydrogen

Cluster 5 is the largest cluster analyzed with 3,794 papers. The word cloud and the five countries that published the most in cluster 5 can be seen in Figure 20 and Figure 21, respectively.

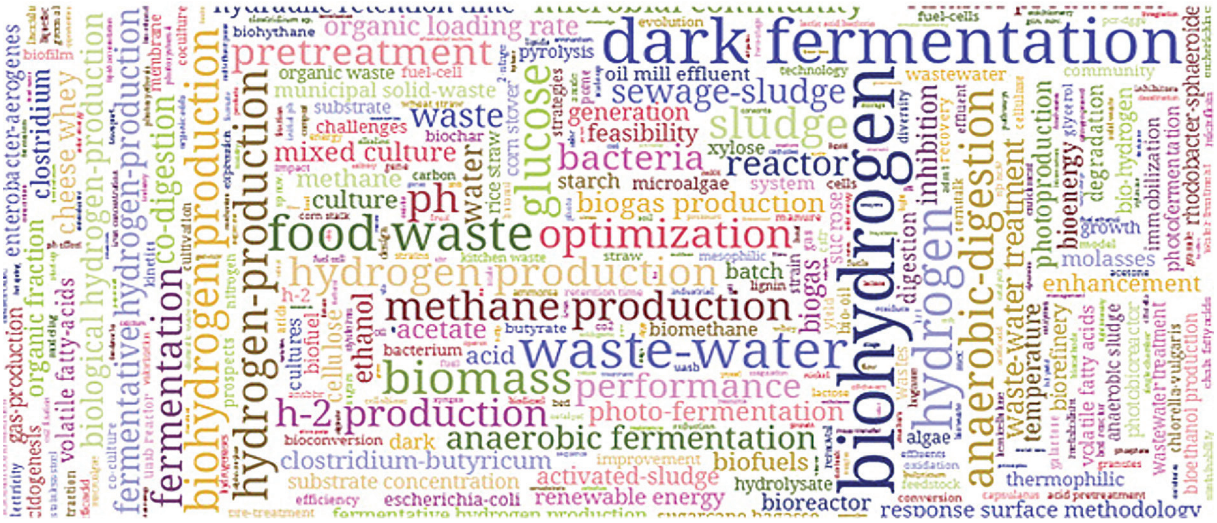

Figure 20: Word cloud of cluster 5

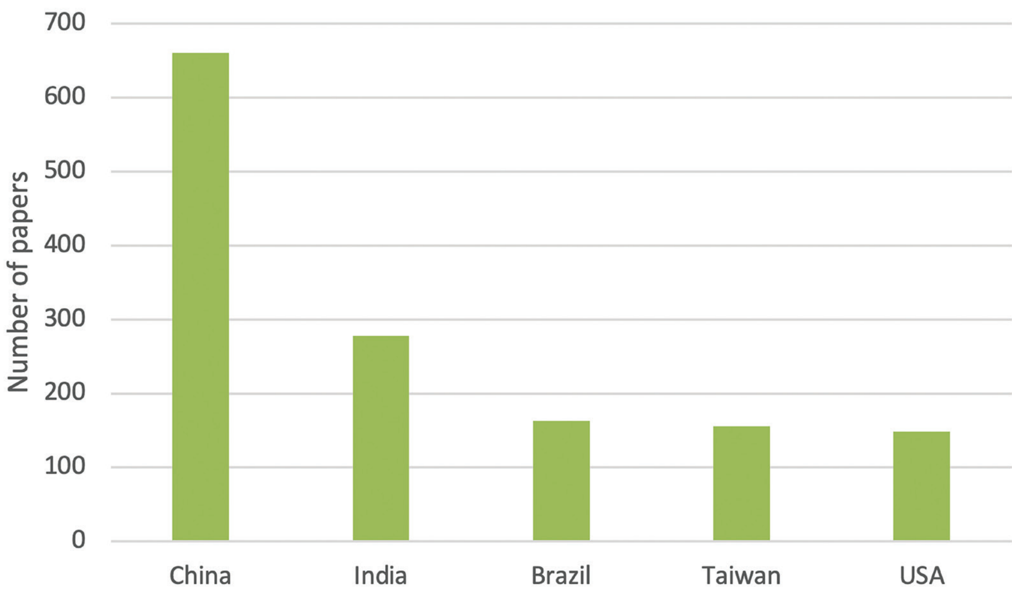

Figure 21: Five countries that published the most in cluster 5

Cluster 5 deals primarily with biological processes for the production of **hydrogen**, or as it is often cited in the cluster, about the production of biohydrogen. As in cluster 4, several papers discuss different starting raw materials, many of them in the form of waste, such as **industrial effluents**, **food waste**, and **sewage sludge**. Other raw materials that are frequently cited are **glucose**, **sucrose**, and **xylose**. **Biohydrogen** production is analyzed by considering several processes, such as **dark fermentation**, **photofermentation**, and **anaerobic digestion**.

The analysis of the countries that publish the most in cluster 5 showed that Brazil is in the third position, behind China and India.

4.2.6. Cluster 6: Hydrogen from glycerol

Cluster 6 is the smallest cluster analyzed with 608 papers. The word cloud and the five countries that published the most in cluster 6 can be seen in Figure 22 and Figure 23, respectively.

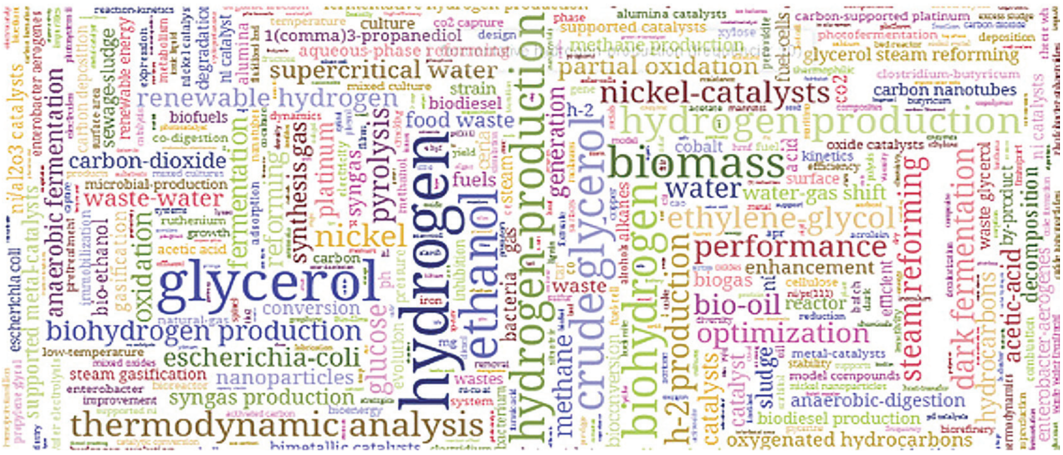

Figure 22: Word cloud of cluster 6

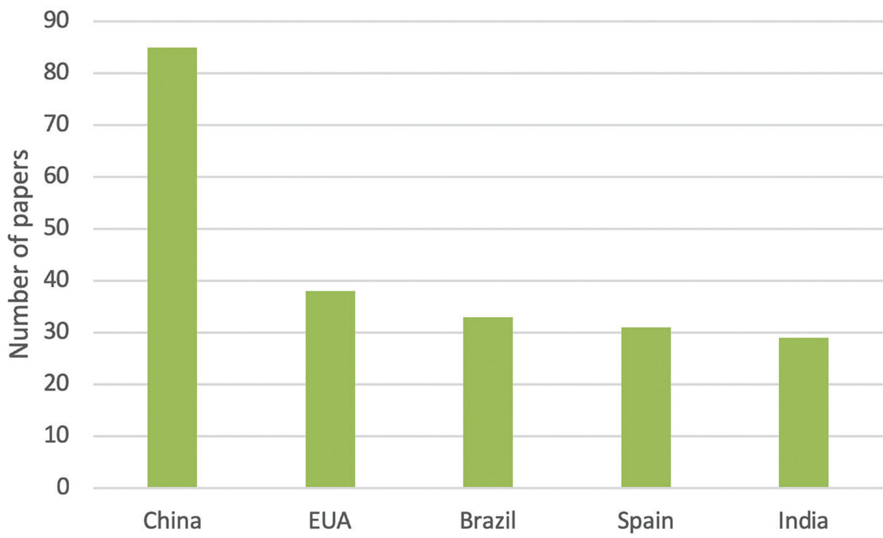

Figure 23: Five countries that published the most in cluster 6

Cluster 6 is quite concentrated, showing that the papers tend to discuss very similar topics. The main focus of cluster 6 is the production of hydrogen from glycerol by processes such as steam reforming and autothermal reforming. Discussions on the use of glycerol are often contextualized under the fact that glycerol is a co-product of biodiesel production, generated in large quantities and with high potential for use in hydrogen production. As in the previous cluster, Brazil stands out among the countries that publish the most in the cluster, behind China and the USA.

4.2.7. Cluster analysis

The analysis of the six clusters corresponded to 10,265 papers, which is equivalent to 61.8% of the network. This means that several other topics were present in the network, but formed smaller clusters or connection clusters, i.e., those that deal with more than one of the topics analyzed.

From the temporal analysis of the clusters (Figure 24), highlights include the strong participation of the biohydrogen cluster since 2007 and the accelerated growth of the electrolysis cluster as of 2011, which exceeded the number of biohydrogen papers in 2020.

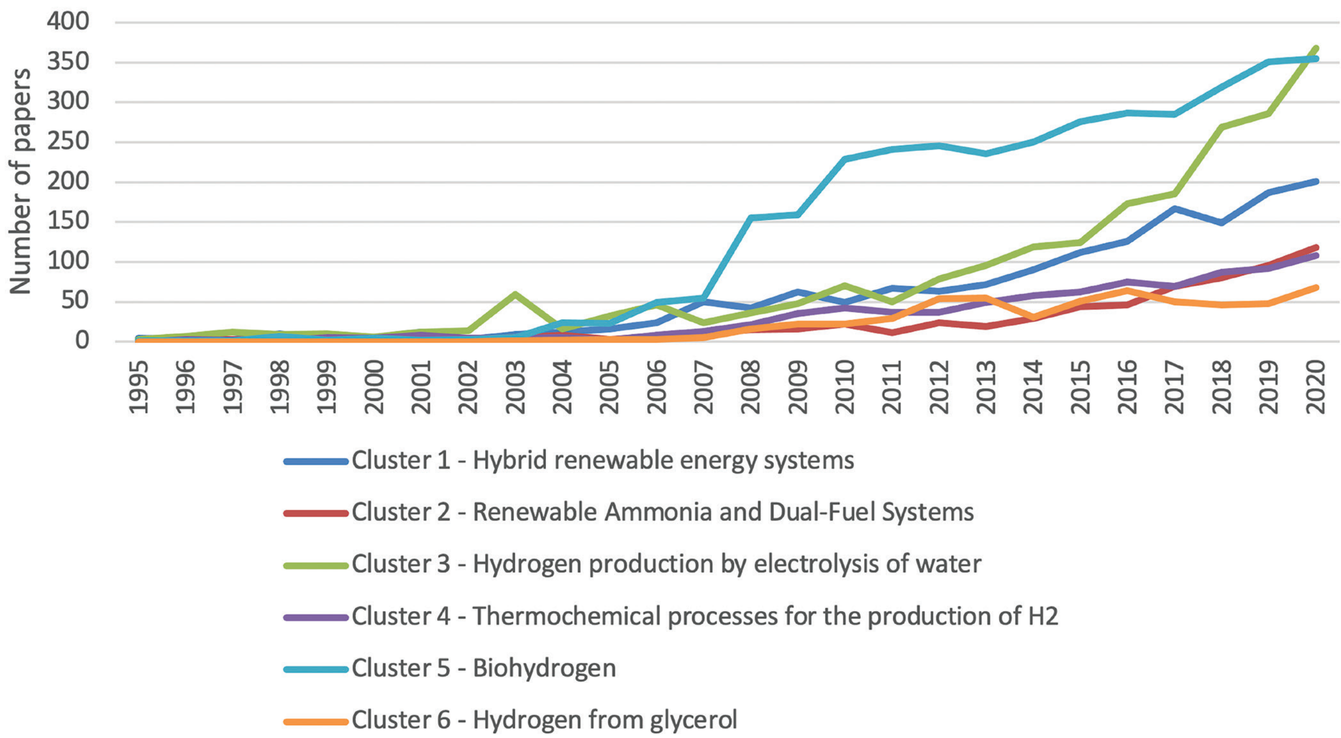

Figure 24: Temporal analysis of papers in the clusters

The data on the countries that published the most in each cluster showed the strong participation of China and the USA in scientific papers on renewable hydrogen, being present among the five countries that published the most in the six clusters analyzed. Another country worth mentioning is India, with a strong presence in clusters 2 (renewable ammonia and dual-fuel systems), 4 (thermochemical processes for H2 production), and 6 (hydrogen from glycerol). Brazil was highlighted in two clusters, 5 (biohydrogen) and 6 (hydrogen from glycerol), as well as South Korea, Spain, and Italy, which also appear in two clusters.

The next section will discuss more deeply the distribution of each country's participation in the generated network papers, focusing on Brazilian publications.

4.3. Analysis by country

Figure 25 shows the 20 countries that most published on renewable hydrogen in the network, with Brazil in the 17th position. Figure 26 shows the map of the number of papers on renewable hydrogen by country.

Results for the complete network reflect the results seen in the cluster analysis. China, the USA, and India appear as the countries that have published on the subject the most. There was also significant participation of Asians countries and the low participation of South America, with only Brazil as a representative among the top 20.

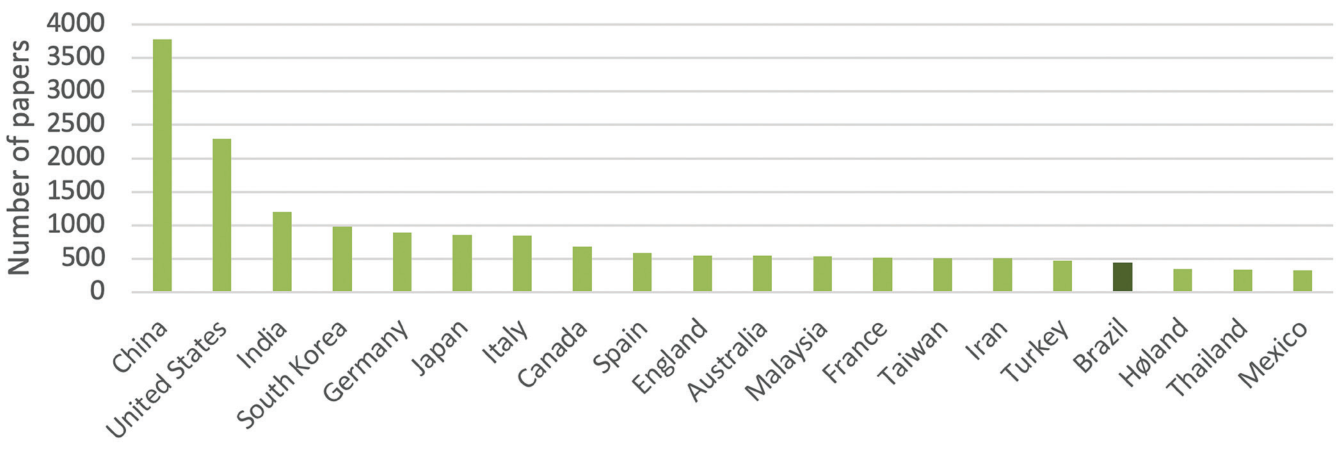

Figure 25: VTwenty countries with the most scientific papers in the renewable hydrogen network

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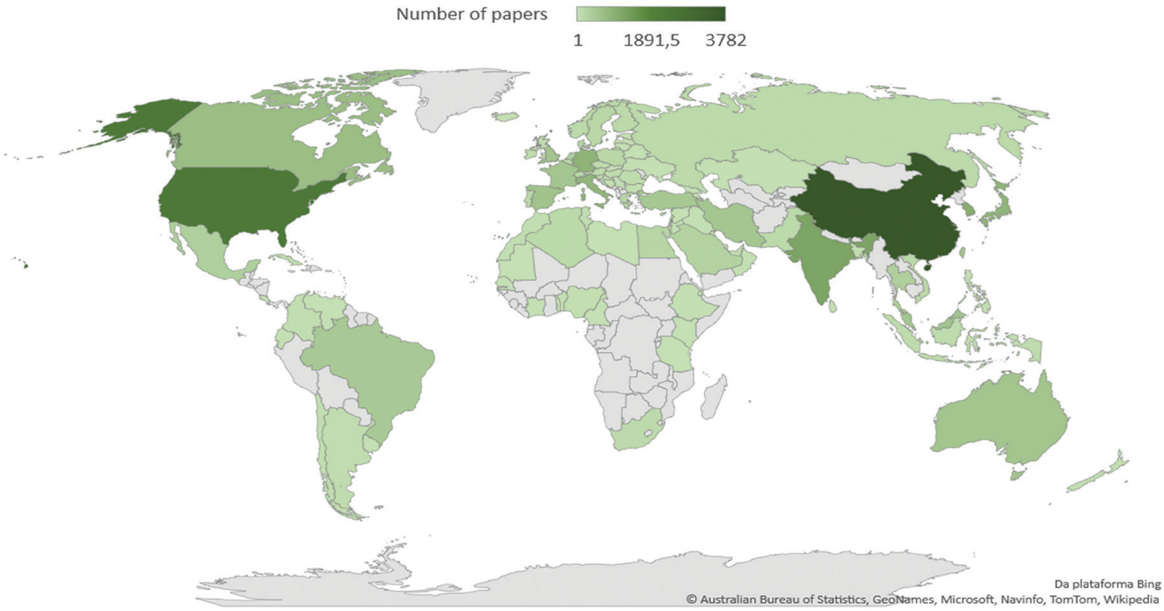

Figure 26: Map of the number of papers on renewable hydrogen.

4.3.1. Brazilian papers

Brazil presented a total of 440 papers in the RH2 network, 163 of which are in cluster 5 (biohydrogen) and 33 in cluster 6 (hydrogen from glycerol). Out of the 440 papers, 137 were done in partnership with other countries. Figure 27 presents the ten countries that most partnered with Brazil in the RH2 network, and Figure 28 the word cloud of Brazilian papers.

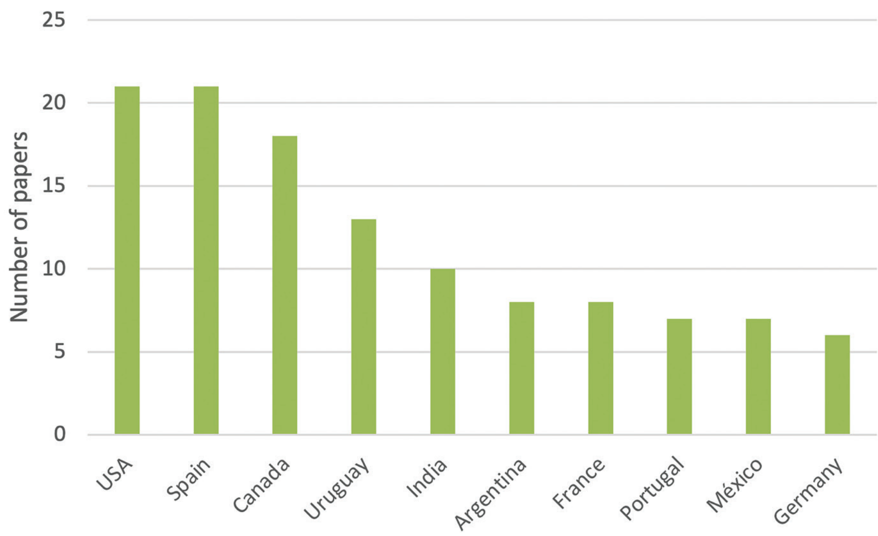

Figure 27: 10 countries with the most frequent partnerships with Brazil in the generated network

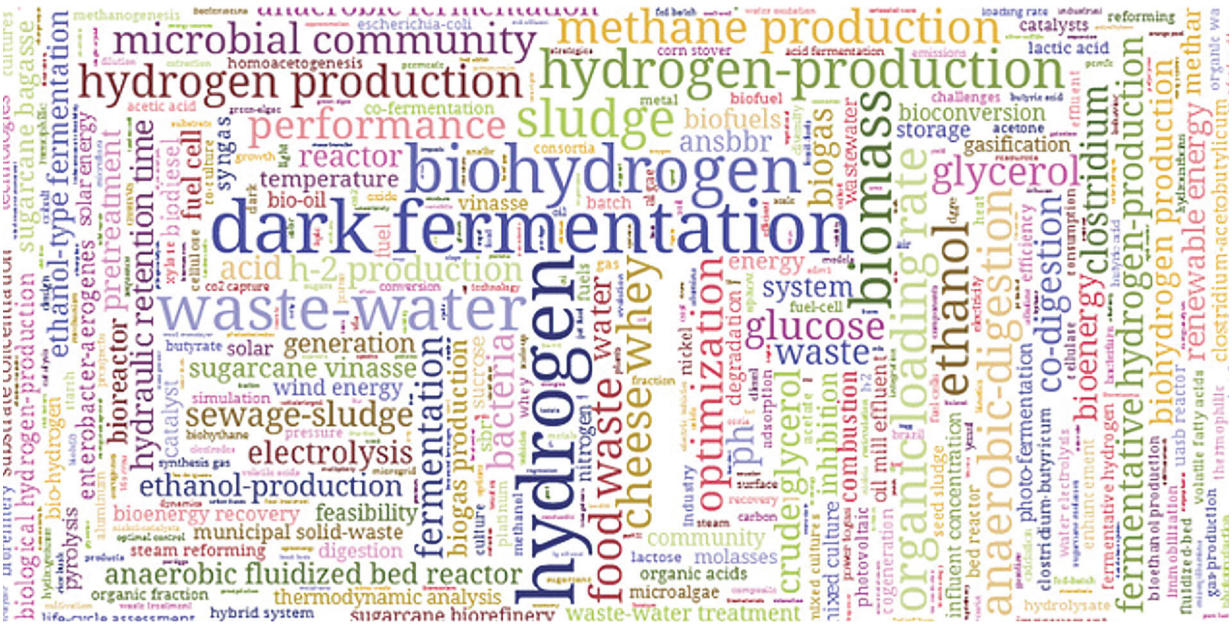

Figure 28: Word cloud of Brazilian papers in the generated network

Figure 28 reflects part of what had already been noted in the cluster analysis, which is the presence of Brazil in **biohydrogen-related** topics. The five most cited keywords are **hydrogen** (98), **dark fermentation** (90), **biohydrogen** (73), r**esidual effluents** (68), and **biomass** (54).

Section 4 presented the data regarding scientific papers on renewable hydrogen, and section 5 will present information on the production of patents.

5. Overview of global patent production on renewable hydrogen

This section aims to present the panorama on the production of patents on renewable hydrogen from an experimental study[6] with the EspaceNet database.

The EspaceNet database was chosen because it includes among its search attributes the CPC code - *Co-operative Patent Classification*, which contains section **Y02** that encompasses **technologies or applications for mitigation or adaptation to climate change**. Under this predetermined set of patents, a search was conducted using the term **"hydrogen"** and **"production"** in the patent titles. This choice simplified the analysis as it did not depend on a controlled vocabulary to search for hydrogen patents related to sustainable aspects.

The next subsections present an overview of the set of patents surveyed, an overview of the most frequent International Patent Classification codes (IPCs), and an analysis of the characterization of the technology areas of patents by topical clusters.

Esse é o número 7

[6] Unlike the analysis of scientific papers, for which CGEE already has consolidated methodologies and tools, the analysis of patents was the result of an experimental study aimed at developing improved techniques for studies on patent records.

5.1. Overview of the patents surveyed

The experimental study with the EspaceNet base allowed a survey of **6,073 patents** related to renewable hydrogen. Figure 29 shows the word cloud of the patent titles. To improve the visualization of the cloud, we removed the words **hydrogen** and **production** - because they appeared in large numbers - as well as stop words: method, system, device, apparatus, producing, process, thereof, and preparation. As a result, it was possible to identify some topics, such as the **water electrolysis** process - **water**, **electrolysis**, and **electrolytic** -, the use in fuel cells - **fuel** and **cell** -, storage - **storage** -, the presence of catalysis processes - **catalyst** - and thermochemical processes - **reforming** and **thermochemical**.

Figure 29: Word cloud of renewable hydrogen patent titles

Figure 30 presents the evolution of the number of patents over the years. To generate the graph in Figure 30, the **year of publication** field was used. Some patents have more than one year of paper because they were published in different countries or because they have received some reformulation. For these cases, the patents were accounted for each year in which there was a new filing. In order to construct the graph, patents filed since 1970 were considered, due to the fact that the 1970s saw strong growth in deposits in this topic as a consequence of the oil shocks of 73 and 79, as shown in the graph of Figure 31. Between the years 2001 and 2006, it is possible to identify a second wave of growth and a third wave since 2016 (Figure 30). The lower number of patent deposits in 2021 is due to the fact that the data was collected in October 2021.

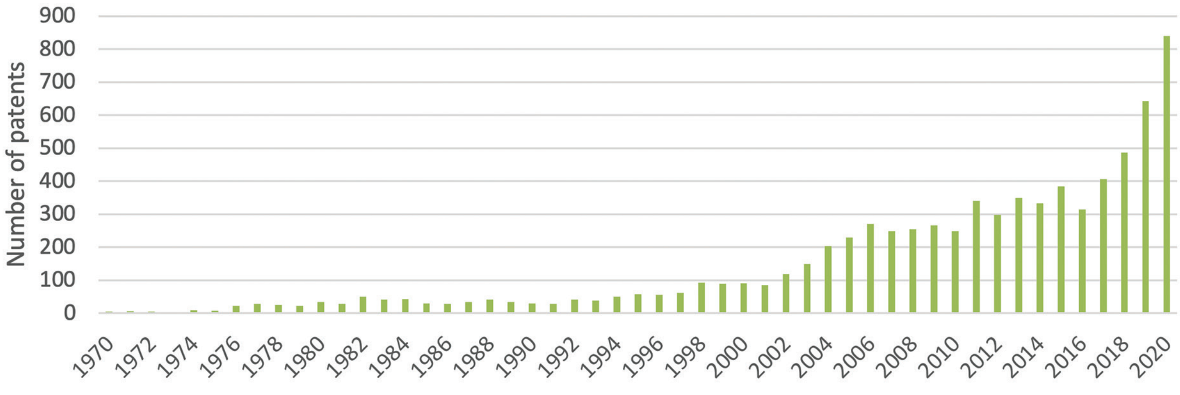

Figure 30: Evolution of the number of patents over time from 1970 onwards

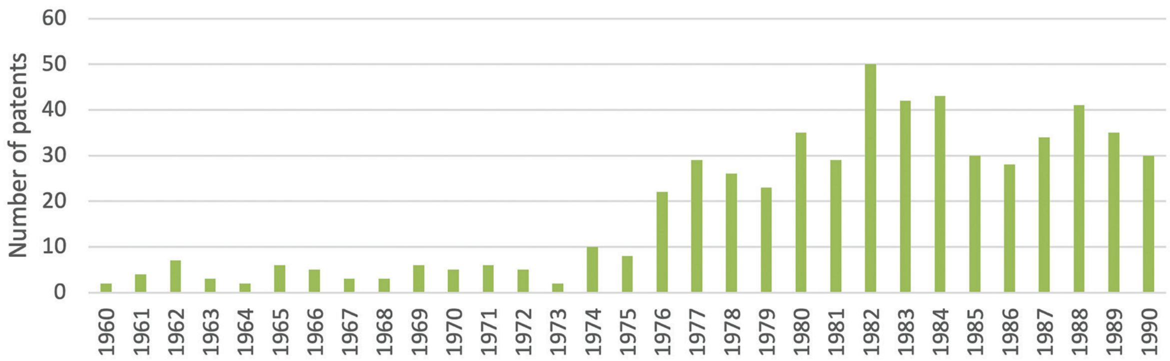

Figure 31: Evolution of the number of patents over time in the period 1960 to 1990

Figure 32 shows the 12 countries or organizations that received the greatest number of patent applications. The top five include China, Japan, and the USA, as well as the World Intellectual Property Organization (WIPO) and the European Patent Office (EPO).

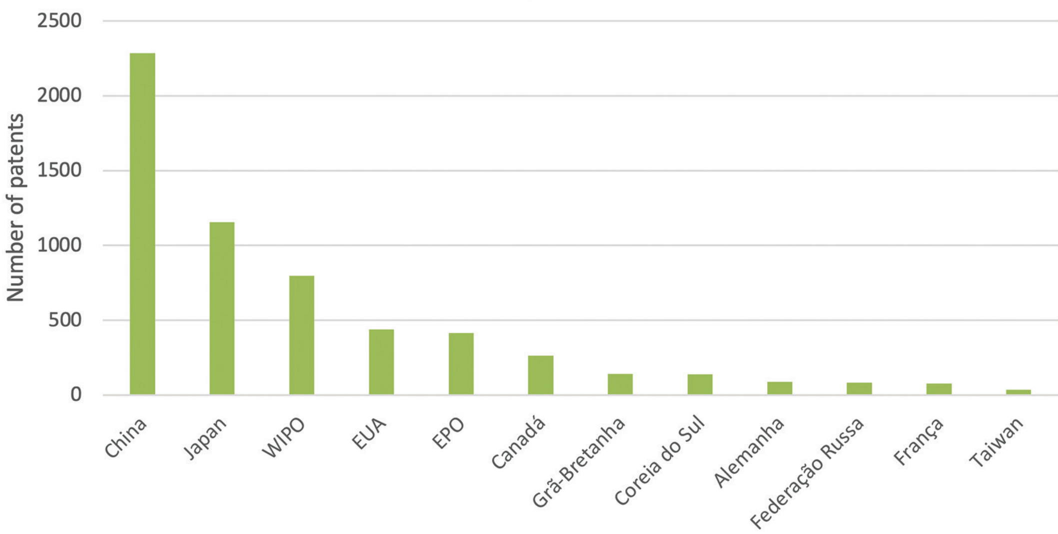

Figure 32: Countries where patents have been filed

5.2. Main IPC codes of the patents surveyed

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The International Patent Classification (IPC) code provides a hierarchical system of language-independent symbols for the classification of patents and utility models according to the different areas of technology to which they belong (WIPO, 2021). A patent can have one or more IPC codes following the applicants' choice.

Analyzing the IPC codes of a patent is a way to identify the subjects it describes. Thus, the ten most frequent IPC codes were identified in the set of patents surveyed, regardless of whether they appear in isolation or aggregated with other codes. Table 2 presents the description of the IPCs codes by subclass, group, and subgroup, i.e., by the most specific levels of classification. An example of a complete classification can be seen in Figure 33 for code c25b1/04.

Table 2: Most frequent CPI codes by subclass, group, and subgroup level. Source: Espace Net (2021)

IPC	Subclass	Group	Subgroup	Occurrence
c25b1/04	Electrolytic or Electrophoretic processes for non-metals	Electrolytic production of inorganic compounds or non-metals	by water electrolysis	1035
c01b3/04	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation, and purification)	by decomposition of inorganic compounds, e.g., ammonia	758
h01m8/06	Processes or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	Fuel cells	Combination of fuel cells with means for reagent production or waste treatment	670
c01b3/38	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation and purification)	using catalysts	565
c01b3/06	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation, and purification)	by reaction of inorganic compounds containing electropositively bound hydrogen, e.g., water, acids, bases, ammonia, with inorganic reducing agents	563
c01b3/08	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation, and purification)	Production of hydrogen or gaseous mixtures containing a substantial proportion of hydrogen	388
c01b3/02	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation, and purification)	Production of hydrogen or gaseous mixtures containing a substantial proportion of hydrogen	370
c25b9/00	Electrolytic or Electrophoretic processes for non-metals	Cells or groups of cells	-	353
c01b3/32	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation, and purification)	by reaction of gaseous or liquid organic compounds with gasification agents, e.g., water, carbon dioxide, air	344
c01b3/00	Inorganic Chemistry - Non-metals	Hydrogen (mixtures, separation and purification)	-	317

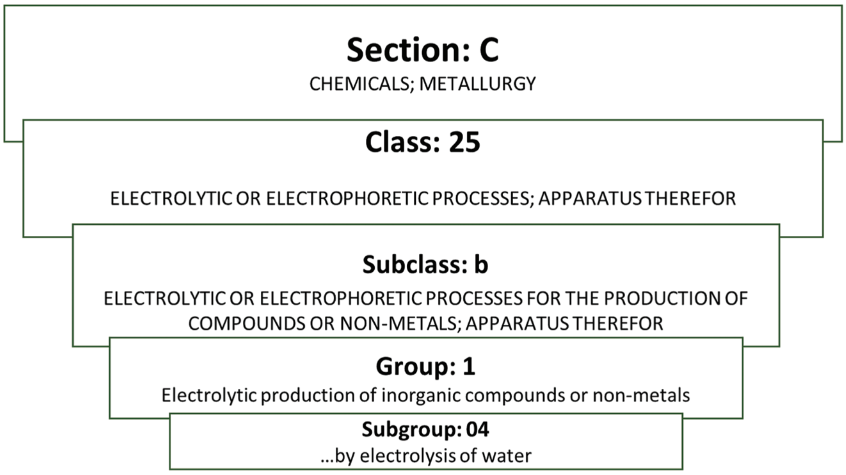

Figure 33: Technology area hierarchy of CPI C25b1/04

As seen in Table 2, the most frequent code refers to the **production of hydrogen by water electrolysis**. Also, seven of the ten most frequent codes present the classification up to group c01b3, which describes processes involving hydrogen gas. This was expected, as it is a technology category that cuts across several processes. The third most frequent code describes the application of renewable hydrogen, namely fuel cells. For example, of the 670 occurrences of the code **h01m8/06** (fuel cells) in patents, 369 contain the phrase **"hydrogen production"** in their title, which could suggest a hydrogen production process for application in fuel cells.

It is, thus, important to analyze how the IPC code sets co-occur in the patents. This analysis is presented in the next section.

5.3. Network characterization - Analysis of IPC code clusters

To characterize different groups of technologies in the surveyed records, a co-occurrence analysis was performed between the IPC codes of the patents. Similar to what was done with the analysis of scientific papers, CGEE's own software identified different classes of modularity in the **code network**. It is important to note that, in order to analyze the different groups of technologies, a network was built that focused on how the IPC codes of the patents grouped together and not the patents themselves.

Through the analysis of the network of codes, it was possible to identify seven clusters of technology areas. For each of them, the three codes with the highest eigenvector centrality value were identified, i.e., the three codes that best represent the cluster. Also, patents that had at least one of the three codes were checked. To characterize the technological cluster - in addition to the description of the IPC code by the Espace Net base - **the word cloud of the patent titles** was used, with the support of the **ISES WG RH2 experts**. Please note that, for all the clouds below, we removed the words **hydrogen** and **production** as well as the following stop words:

method, system, device, apparatus, producing, process, thereof, and preparation.

The next subsections will present the seven clusters, the number of patents that have the three most representative codes, and the word cloud of each title.

5.3.1. Cluster 1 - Electrolysis

Figure 34 presents the word cloud of cluster 1. The most representative IPCs (c25b1/04, c25b9/00, c25b1/02) retrieved 1,278 patents. The most frequent words in the titles are **water**, **electrolysis**, **power**, and **electrolytic**. Based on these words and others such as **wind**, **solar and photovoltaic**, this cluster contains mainly water electrolysis processes for the production of hydrogen from renewable sources.

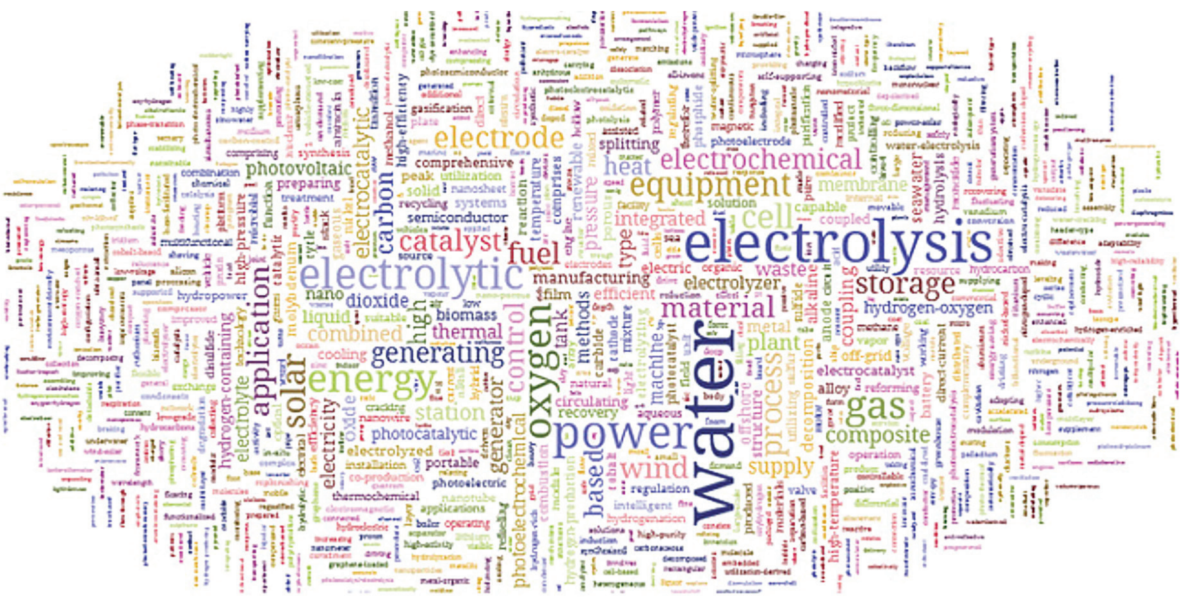

Figure 34: Word cloud of the electrolysis cluster

5.3.2. Cluster 2 - Fuel Cells

Figure 35 presents the word cloud of cluster 2. The most representative IPC codes (h01m8/06, c01b3/02, c01b3/38) retrieved 1,532 patents. The most frequent words in the titles are **fuel**, **cell**, **gas**, and **reforming**. Associated with other words, the cloud presents characteristics of RH2 application as **fuel cell** and **vehicle** (cars powered by **fuel cells**) and production, such as r**eforming** and **methanol** that can refer to the production of RH2 from methanol-reforming.

Figure 35: Word cloud of the fuel cell cluster

5.3.3. Cluster 3 - Catalytic processes

Figure 36 presents the word cloud of cluster 3. The most representative IPCs (c01b3/04 b01j37/02 c01b3/40) retrieved 1,039 patents. The most frequent words in the titles are **catalyst**, **water**, **photocatalytic**, and **gas**. Along with words like **preparation** and **composite**, it is possible to identify the cluster containing **catalytic processes** with an emphasis on **photocatalysis**.

Figure 36: Word cloud of the catalytic processes cluster

5.3.4. Cluster 4 – Thermochemical processes

Figure 37 presents the word cloud of cluster 4. The most representative IPC codes (c01b3/06, c01b13/02, c01b3/08) retrieved 977 patents. The most frequent words in the titles are **water**, **hydrolysis**, **oxygen**, and **gas**. Joint analysis with the words: **sodium**, **borohydride**, and **aluminum** show specific processes for hydrogen production through the hydrolysis of sodium borohydride and aluminum compounds. Words such as **thermochemical** and **gasification** extend the analysis to other types of processes.

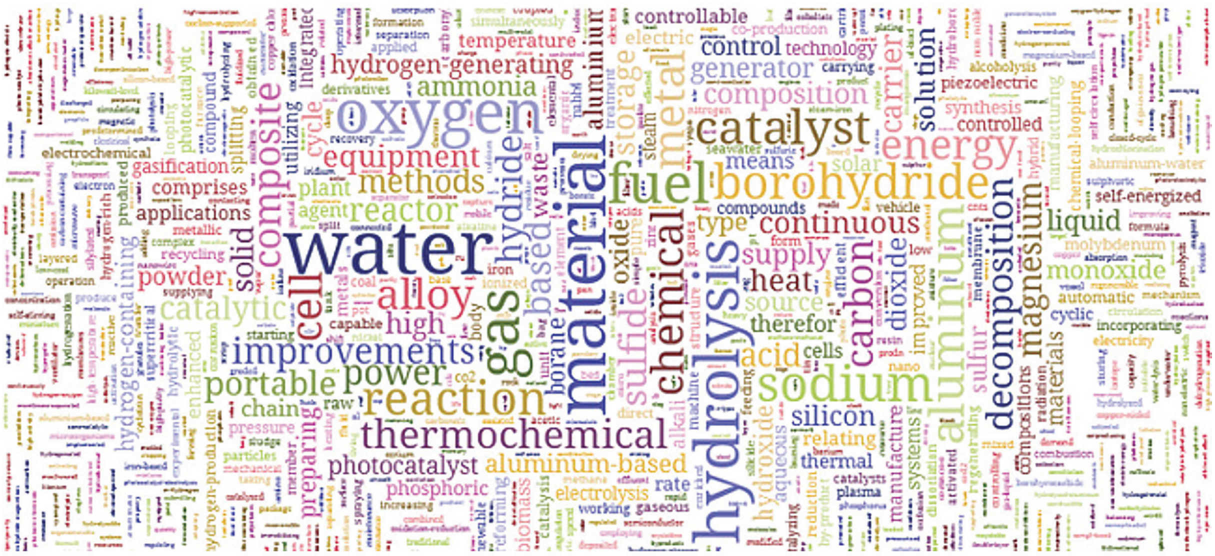

Figure 37: Word cloud of the catalytic processes cluster

5.3.5. Cluster 5 - Biohydrogen

Figure 38 presents the word cloud of cluster 5. The most representative IPCs codes (b09b3/00 c12p3/00 c12m1/00) retrieved 134 patents. The most frequent words in the titles are **gas**, **methane**, **waste**, and **fermentation**. Along with words such as **organic**, **biomass**, **biological** and **microbial**, it is possible to identify that this cluster consists of **biological processes** for the production of RH2.

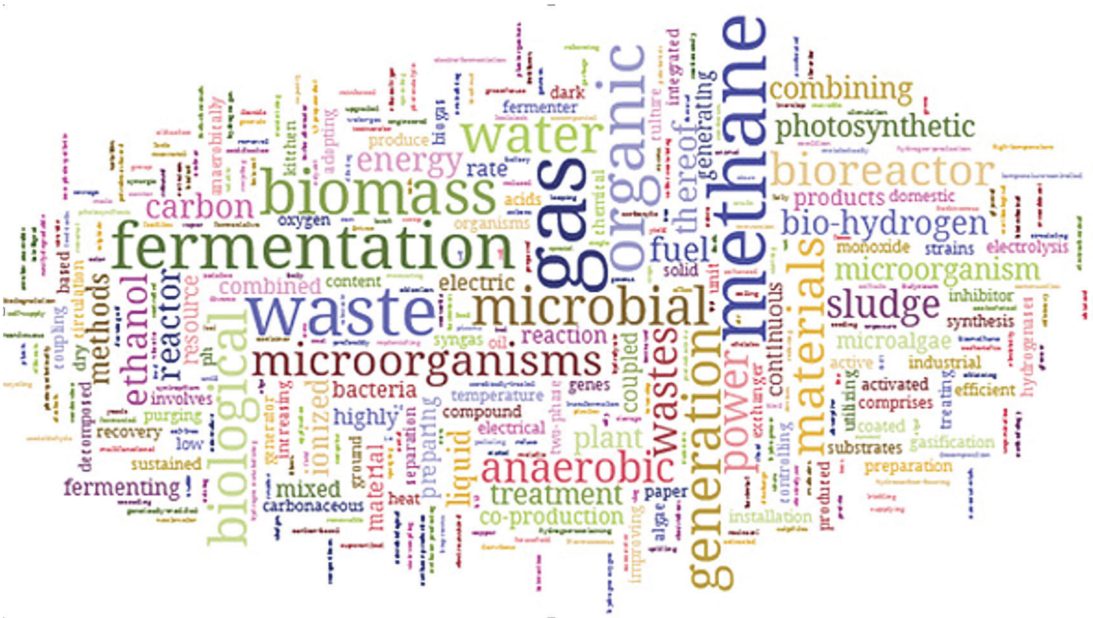

Figure 38: Word cloud of the biohydrogen cluster

5.3.6. Cluster 6 - Storage

Figure 39 presents the word cloud of cluster 6. The most representative IPC codes (c01b3/00 f17c11/00 c22c1/00) retrieved 419 patents. The most frequent words in the titles are **storage**, **alloy**, **material**, and **battery**, with the significant presence of the first 2 - **storage** and **metal alloys**. Cluster 6 groups technologies that involve technological areas related to hydrogen storage.

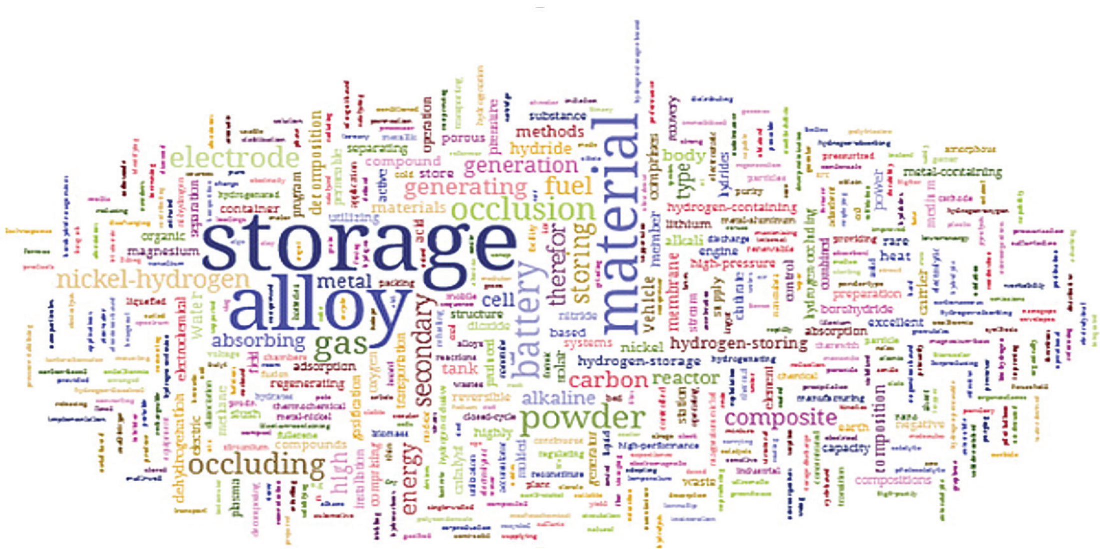

Figure 39: Word cloud of the hydrogen storage cluster

5.3.7. Cluster 7 - Combustion Engines

Figure 40 presents the word cloud of cluster 7. The most representative IPC codes (f02m25/12 f02b43/10 f02m21/02) retrieved 108 patents. The most frequent words in the titles are **engine**, **combustion**, **internal**, and **gas**. Cluster 7 is interpreted as a cluster of **internal combustion engines**.

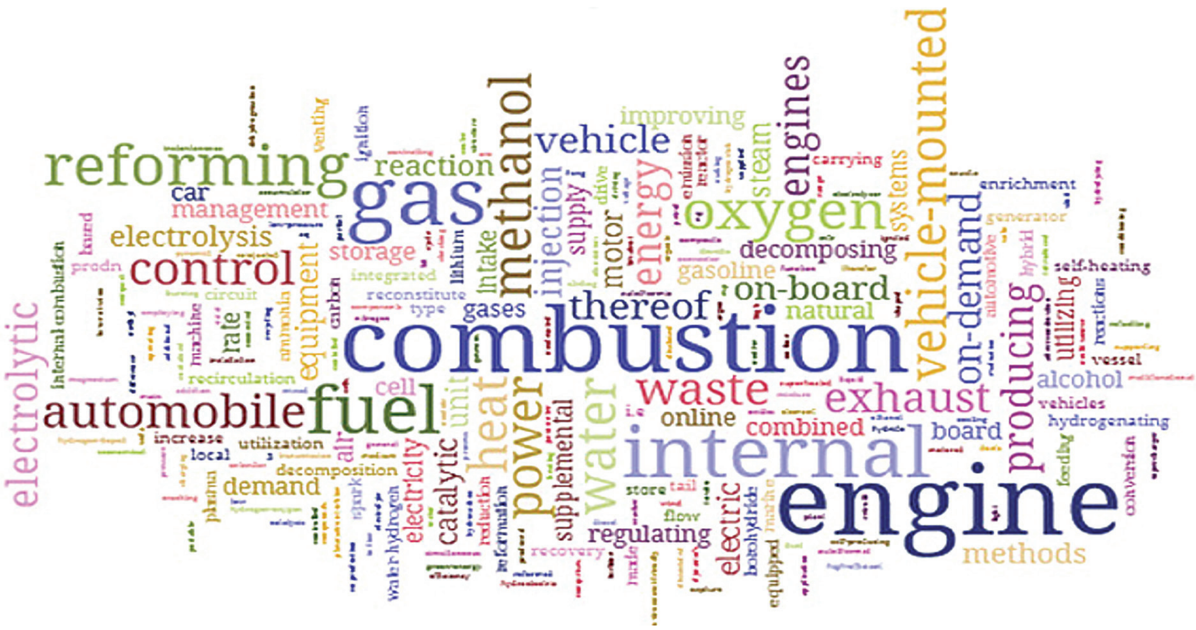

Figure 40: Word cloud of the internal combustion engine cluster

5.4. Final considerations on the patents

Patent analysis clearly showed the prevalence of water electrolysis as a method to obtain renewable hydrogen. Nevertheless, there was a strong presence of codes related to other processes, such as biological and, especially, thermochemical processes. The analysis also emphasized a specific application of RH2, which is its use in fuel cells.

As stated at the beginning of section 5, the methodology presented for the investigation of patents is still experimental and will be further developed in the next editions of the ISES Report. In this sense, it is important to mention some limitations of the analysis: (1) records gathered from only one database, (2) search considering only patents under the umbrella of the CPC code Y02, and (3) analysis without the patent abstracts.

6. Overview of renewable hydrogen projects

This section aims to present the panorama of renewable hydrogen production projects. The basis used for this survey was the IEA Hydrogen Projects Database 2021 (IEA, 2021b) produced by the International Energy Agency and updated to October 2021. The database covers all projects that have been commissioned since 2000 for the production of hydrogen for energy mitigation or climate change purposes. Projects in planning or construction are also included.

For the overview of **renewable hydrogen** projects, units that had fossil resources as raw materials were disregarded, regardless of carbon capture. This filter identified **907 projects** that will be analyzed in the next subsections.

6.1. Overview of renewable hydrogen projects

The IEA database allows filters by hydrogen production technology, as shown in Table 3. Figure 41 presents the distribution of projects by technology grouped by biomass conversion technologies. Figure 41 clearly shows the prevalence of electrolysis projects for RH2 production.

Table 3: Technologies made available in the IEA database (IEA, 2021b)

General Technology	Specific Technology
Water Electrolysis	Alkaline Electrolysis
	Proton exchange membrane electrolysis
	Solid oxide electrolysis cells
	Electrolysis unknown*
Biomass	Biogas reforming
	Biomass gasification
	Pyrolysis of methane
	Microbial fermentation
	Waste gases from biofuel production
	Waste gasification
	Refurbishment of waste
	Various**

* Type of electrolysis not reported
**Combination of processes

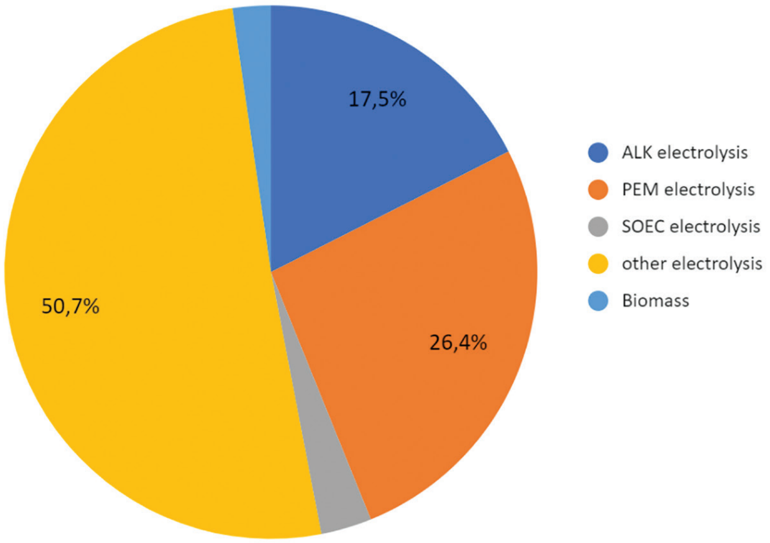

Figure 41: Distribution of the type of technology among projects

Figure 42 presents the 15 countries with the greatest number of projects in RH2 and Figure 43 presents the map with the distribution of projects in the world. It is possible to verify the strong European presence. The USA, Australia, and China also stand out with over forty registered projects.

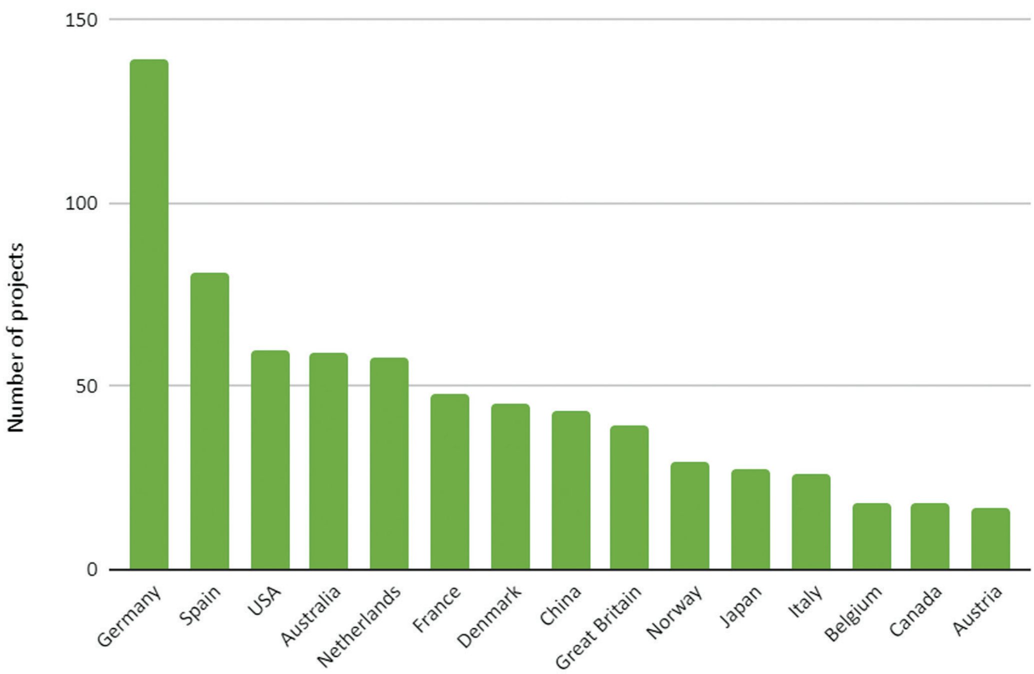

Figure 42: 15 countries with the most projects in RH2

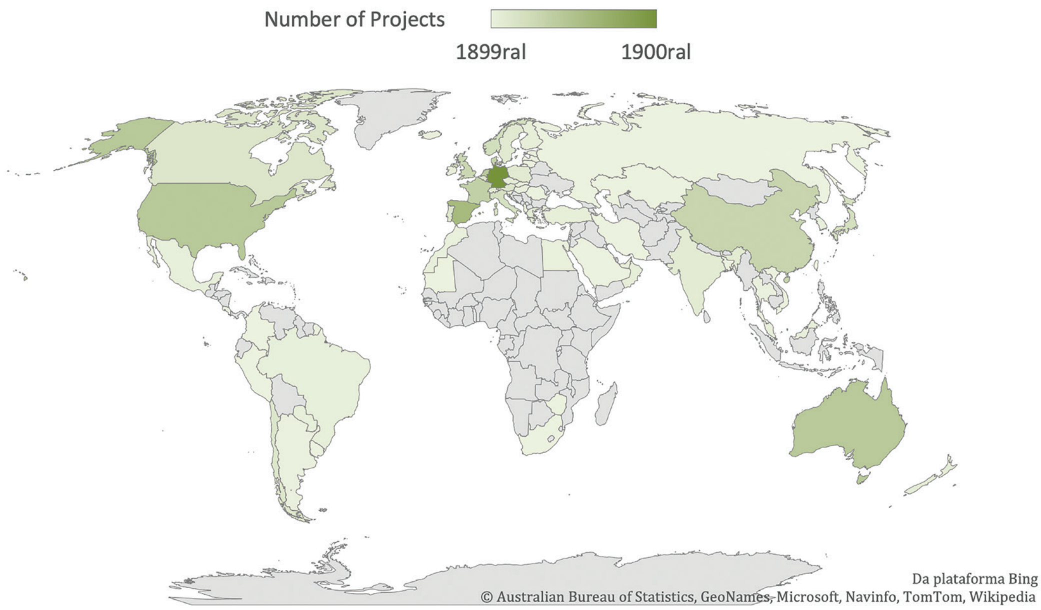

Figure 43: Map of the number of projects by countries in the world

Since the reported capacities of the plants vary considerably, an analysis of the accumulated reported capacity per country was performed. Figure 44 presents the 15 countries with the highest cumulative reported capacity in Nm3H2 /h, and Figure 45 presents the map with the distribution of cumulative reported capacities worldwide. It is important to note that of the 907 RH2 projects, **153 did not report their capacities**. As a result, Figure 44 counts on data from 83.1% of the projects. It is possible to see major differences between Figure 42 and Figure 44. Although there is a strong European presence, other countries, such as Kazakhstan, Mauritania, Oman, and, in South America, Chile, and Brazil stand out.

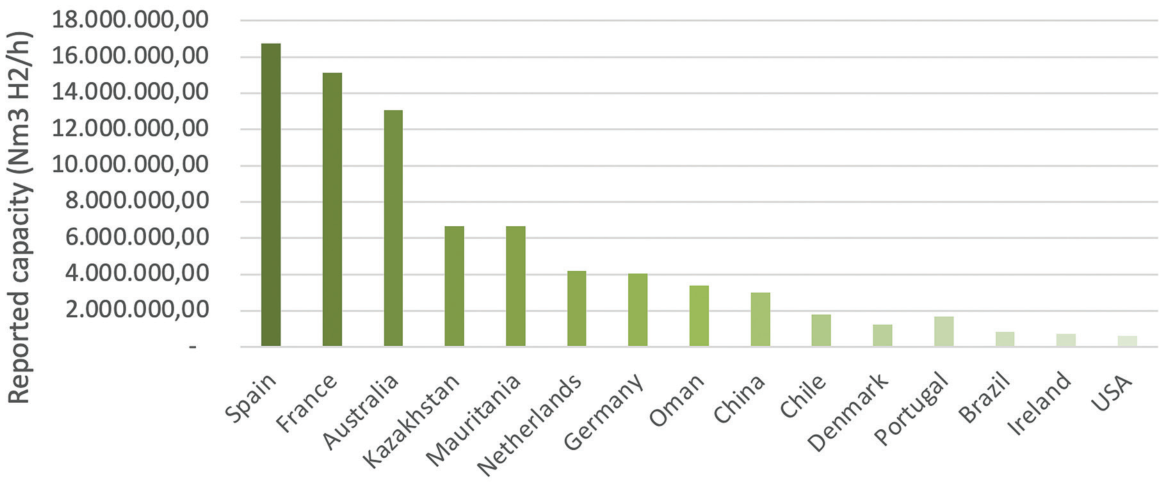

Figure 44: 15 countries with the largest cumulative RH2 production capacities

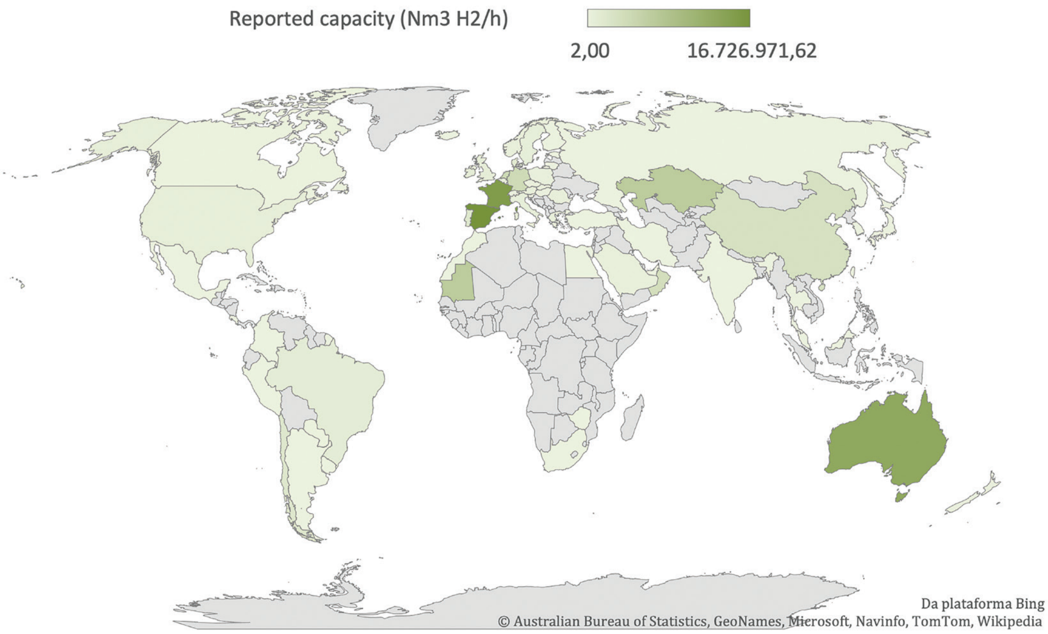

Figure 45: Map with the distribution of accumulated reported capacities in the world

6.2. Brazilian projects

The IEA database identified four RH2 projects in Brazil. Information regarding the projects is available in Table 4. Three projects are located in the state of Ceará, which has been a hub for renewable hydrogen in the country. Another relevant point is the use of offshore wind energy as a type of renewable energy for electrolysis.

Table 4: Brazilian projects in RH2

Project Name	Online date	Technology	Type of electricity	Type of renewable energy	Capacity in ktH2/year
Marítimo Dragão - Qair	2023	Electrolysis - other	Dedicated Renewable	Offshore wind	Not available
Port of Pecem - Base One	2025	Electrolysis - other	Dedicated Renewable	Hydroelectric Plant	600
Port of Pecem - Base One	2030	Electrolysis - other	Dedicated Renewable	Offshore wind	Not available
Porto do Açu Fortescue Ammonia Project	Not available	Electrolysis - other	Dedicated Renewable	Other/ miscellaneous	52

6.3. Analysis by technology - Electrolysis

The IEA database surveyed some information specific to the different types of technologies for RH2 production. In the case of electrolysis - 886 projects - information on the renewable energy source that will be used in the process was mapped. The graph in Figure 46 shows that photovoltaic solar and wind onshore and offshore are the most used. However, this figure is uncertain as 73% of the projects either do not disclose this information or use other or various renewable energy sources.

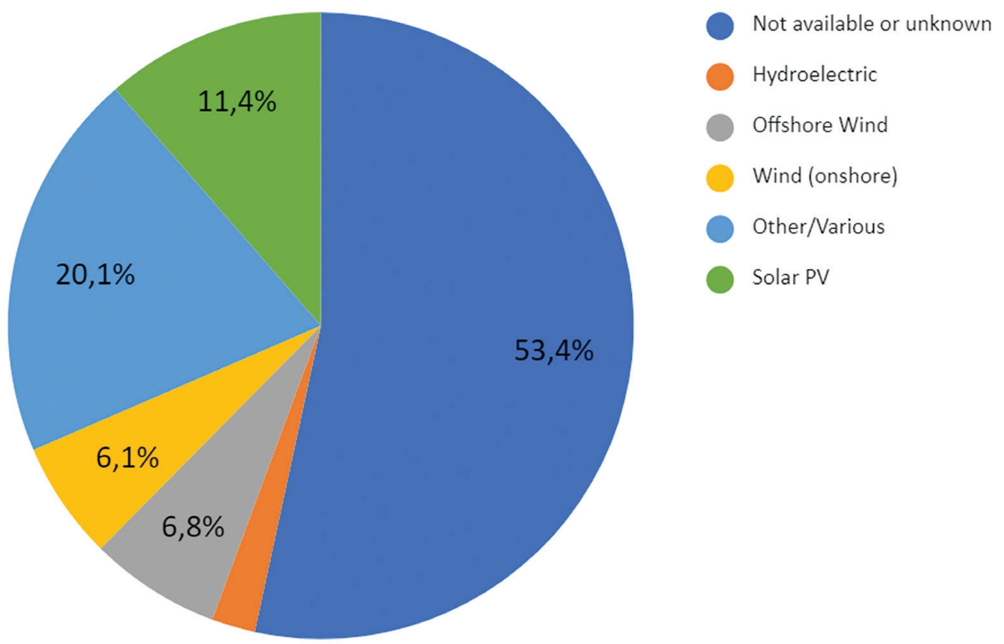

Figure 46: Renewable energy source for electrolysis

6.4. Analysis by technology - Biomass

The IEA database presents "biomass" as one of the technology categories (21 projects), i.e., processes that use biomass as raw material for renewable hydrogen. However, within this broad classification, there are quite different processes. Figure 47 presents the technology breakdown of projects categorized as biomass. Although 24% does not present information, it is possible to verify that thermochemical processes, especially gasification, are more frequent.

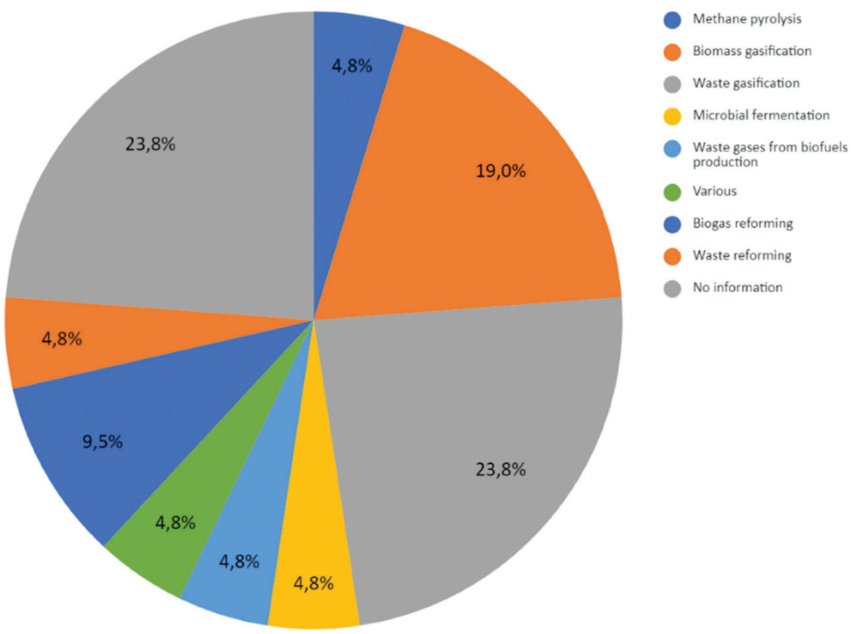

Figure 47: Distribution of different technologies using biomass

6.5. Considerations on the panorama of projects in RH2

Unlike data on scientific papers and patents, information on projects tends to be more difficult to obtain and harmonize. The availability of the IEA database allowed a reliable and broad analysis of the topic, even though some information was missing.

As seen in the patent overview, the water electrolysis process has proven to be the main technology for RH2 production, but not the only one. The next section presents a brief analysis of the production processes by electrolysis and biological processes.

7. General considerations and conclusions

The three overviews presented - scientific papers, patents and projects - contributed to an initial assessment of the maturity of some renewable hydrogen technologies. It is relevant to note that the network and cluster patterns were different for each of the panoramas. As a last analysis, we checked the behavior of two types of hydrogen production technologies: from water electrolysis (electrolytic hydrogen) and from biological processes (biohydrogen). Electrolytic hydrogen was chosen because it is the most present topic in patents and projects. Biohydrogen was chosen because it was the most frequent topic in the analysis of scientific papers and because Brazil was one of the countries that published most on the topic in the generated network.

Figure 48 presents the participation of each of these topics in the analyzed networks. In scientific papers, the biohydrogen cluster represented 22.9% of the network, while electrolytic hydrogen represented 14.9%. Regarding patents, these values were 2.2% for biohydrogen and 25% for electrolytic H2. Finally, in the project analysis the participation of biohydrogen was 0.2% while the electrolytic H2 reached 97.7%.

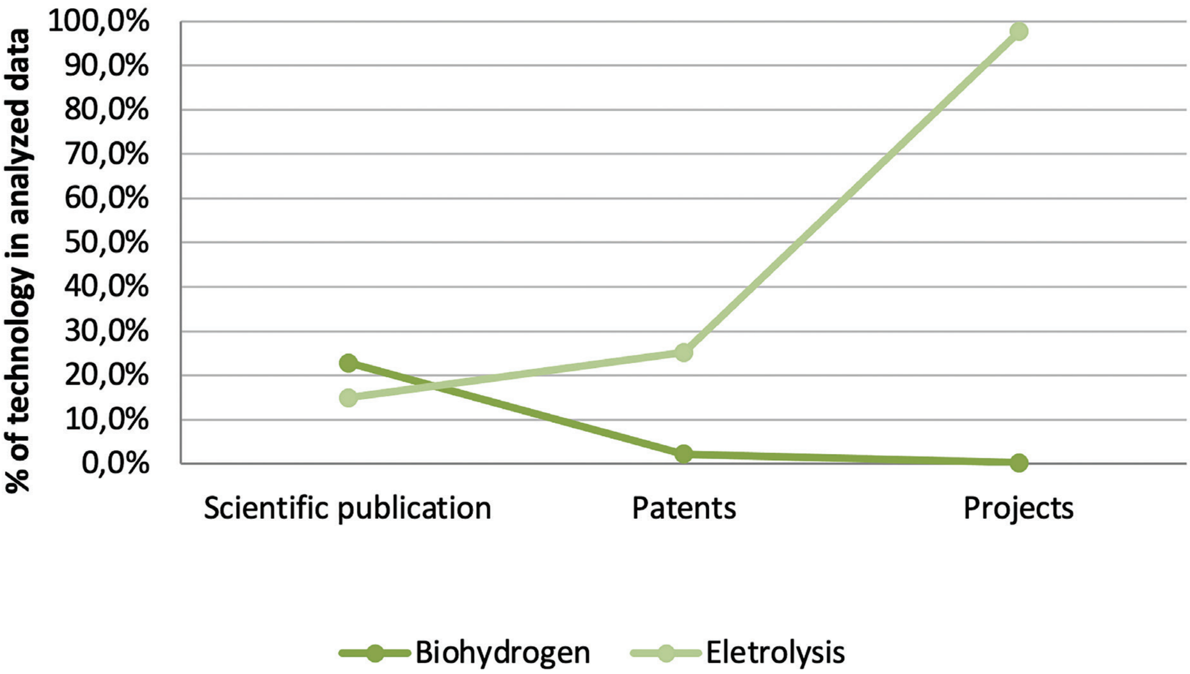

Figure 48: Percentage of data on electrolysis and biohydrogen in each analysis

These results reveal the much higher maturity of electrolysis technologies in comparison to biological processes. However, it is worth noting that the strong presence of biohydrogen in the scientific papers network indicates the investigation of new opportunities, for which Brazil may be one of the main actors.

Overall, the broad analysis on **renewable hydrogen** - not just green hydrogen[7] - was able to capture other opportunities that may represent an important aspect of a future hydrogen economy.

Este é a nota nº 8.

[7] Here indicated as the hydrogen from the electrolysis of water using renewable energy sources.

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