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Green Hydrogen Breakout

The scientific community contribution

Raquel de Assis Pinho

Dissertation

presented as partial requirement to obtain the Master's degree in Information Management

NOVA Information Management School
Instituto Superior de Estatística e Gestão de Informação
Universidade Nova de Lisboa

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GREEN HYDROGEN BREAKOUT

by

Raquel de Assis Pinho

Dissertation presented as partial requirement to obtain the Master's degree in Information Management, with a specialization in Knowledge Management and Business Intelligence

Co-Supervisors: Bruno Damásio and José Almeida Silva

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I declare that I have carried out this academic work with integrity. I confirm that I have not resorted to the practice of plagiarism or any other form of misuse of information or falsification of results during the process of preparing this work. I also declare that I am aware of NOVA Information Management School's Rules of Conduct and Code of Honour.

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ABSTRACT

Renewable energy sources gained highlight in the past years. The United Nations launched the Sustainable Development Goals to push governments towards green initiatives and the International Energy Agency launched the roadmap to achieve net-zero emissions by 2050. Also, several countries created their own roadmaps to lower their green-house emissions. This dissertation focuses on "Green Hydrogen", since it uses renewable sources, like solar and wind, for its production. Although hydrogen is not an energy source by itself, it is a very effective way to store, transport and deploy energy, and it makes renewable energy more competitive. Thus, having a great potential to contribute to a more sustainable and circular economy. We implement a quantitative analysis on all the scientific production about the green hydrogen thematic until the end of 2022 and its progress. The presented work delivers the most promising technological trajectories in the field, highlighting China, Germany, Japan, South Korea and USA as the leading geographies, Japanese institutions as leading institutions in knowledge creation and some interesting interdisciplinary collaborations between institutions. Although the evolving trends focus on production methods' efficiency, the remain challenges focus on the technology efficiency.

KEYWORDS

Green Hydrogen; Renewable Energy; Hydrogen Economy; Circular Economy

Sustainable Development Goals (SDG):

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LIST OF ACRONYMS AND ABBREVIATIONS

NZE	Net-zero emissions
COP21	21st United Nations Climate Change Conference
HER	Hydrogen Evolution Reaction
OER	Oxygen Evolution Reaction
PEM	Proton Exchange Membrane
AEM	Anion Exchange Membrane
Pt	Platinum
Ni	Nickel
EU	European Union
PNEC 2030	Climate Plan 2021-2030

1. INTRODUCTION

In recent years, the global climate crisis turned governments to look for alternative energy sources, to keep giving response to the ever-increasing society's energy consumption. Giving the current scenario, an energy transition is needed, firstly transitioning to renewable energy sources, and then the development of hydrogen economy (Kabir et al., 2023). Hydrogen has the potential to accelerate the transition from an energy paradigm based on the use of fossil fuels to a new landscape where the use of low-carbon energy sources like photovoltaic and wind energy is the norm, also because these forms of energy can be used to produce hydrogen and store energy (Ishaq et al., 2022). Therefore, hydrogen can potentially be strong contributor to a sustainable use of energy. Also, several countries created their hydrogen roadmaps, with manufacturing capacity analysis and selected green hydrogen projects (Wappler et al., 2022), trying to achieve, among several other milestones, the goal of net-zero emissions (NZE) by 2050, established at the United Nations Climate Change Conference (COP21) in 2015.

Although there is already some research made, such as, several hydrogen related projects created according to government' priorities, and journal articles published that explore part of the work done by the scientific community (Raman et al., 2022), it is still missing a combination of all these approaches in a quantitative analysis of knowledge production.

The quantitative analysis of scientific articles made throughout this dissertation addresses the following question: What players and geographies are leading the Green Hydrogen research? The answers revealed by the evidence point to the breakout of this technology and its geographical distribution, such as, the regions that are producing more knowledge; the universities/investigation centres and authors that produce more studies about the theme; the disciplinary distribution of the papers analysed; the most relevant papers in the thematic (based on citations), and the strongest collaborations, both between institutions and countries. These stylized facts shape the knowledge distribution landscape and how this concept is evolving.

The scientific article corpus, constituted by over 1500 articles, was extracted from Web of Science (WoS) taking into consideration the articles whose title, keywords or abstract contain the words "green hydrogen", up to 2022. A quantitative analysis was conducted to cover the objectives mentioned, shaping the knowledge contribution landscape and exposing the necessary future work.

The dissertation is organised as follows. Section 2 describes the hydrogen framework, its different methods of production and technologies as well as its problems such as scalability and cost efficiency (Osman et al., 2022), and the national and international current representation of hydrogen. Section 3 outlines the methodological set-up in all the analysis made and Section 4 presents and discusses those analysis. Section 5 presents conclusions and future work necessary.

2. LITERATURE REVIEW

2.1. Hydrogen Production

Presently, the hydrogen production relies on the use of fossil fuels, and the most used technology by 2021 was natural gas without carbon capture, storage and utilization (IEA, 2022). However, "Green Hydrogen" is a technology that uses renewable sources, like solar and wind, for its production. Thus, having a greater potential to contribute to a more sustainable and circular economy which means it can play an important role to reduce emissions to net zero by 2050 (IEA, 2019). Nevertheless, the efficiency and the environmental degradation are two key points to take into account when associating the green hydrogen contribution to circular economy (Lehmann et al., 2022).

In the context of sustainability and circular economy, there is also interesting literatures, exploring how these two concepts are connected, how they have been evolving, and their importance (de Jesus & Mendonça, 2018; de Jesus et al., 2018; de Jesus et al., 2021).

Based on the analysis made from IEA in Future of Hydrogen in 2019, there is a variety of ways to produce hydrogen that are directly associated to the energy source used to obtain it. They are divided into two main sources: fossil fuels and renewable sources. Inside fossil fuels it is possible to produce using hydrocarbon reforming and hydrocarbon pyrolysis, and in the renewable sources, there is the biomass process and the water splitting, among others (Nikolaidis & Poullikkas, 2017). Although the colour categorization is not yet been internationally agreed (IEA, 2021a), it is worth mentioning (Figure 2.1).

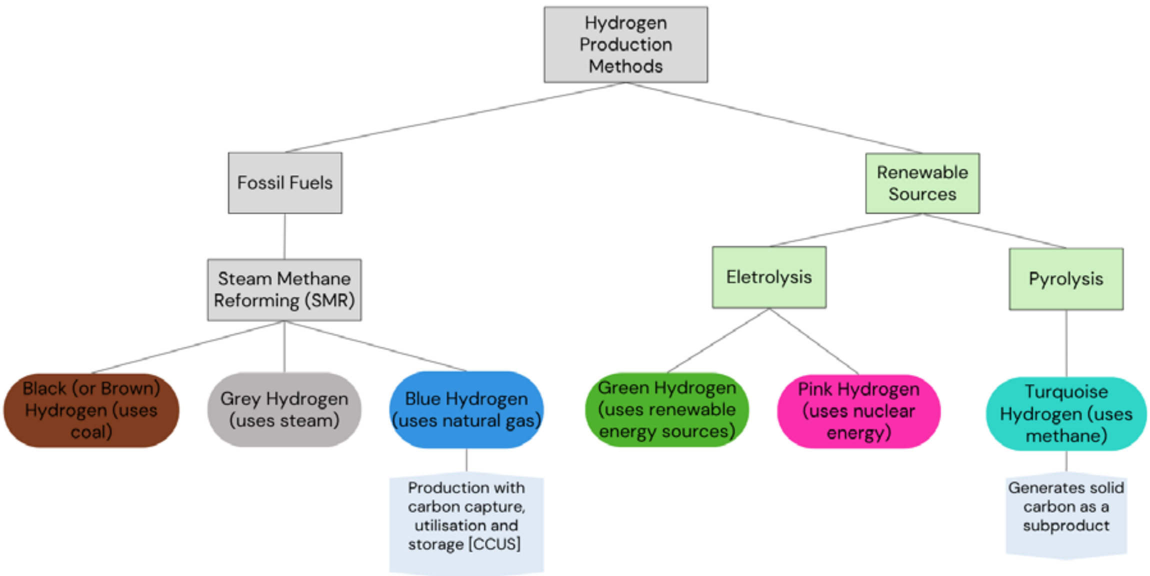

Figure 2.1 – Hydrogen colour categorization (based on UNECE (2022))

Due to the demand of our energy-driven global society and the climate crisis we now live in, the search for sustainable and clean energy is vastly rising. Hydrogen is an abundant element in the planet earth, existing in water and organic materials, but since it does not exist in its elementary form, it is necessary to consume energy in its production process. Regardless, hydrogen is a candidate to explore, especially the green hydrogen, since it can help leading the energy market towards the sustainable goals. Also, since green hydrogen uses the surplus of renewable energy like solar and wind, it can serve to transport energy and store it for significant periods of time, helping with the surplus of renewable energy problem during peak hours, reducing the need for fossil energy, and increasing its competitivity.

2.2. GREEN HYDROGEN PRODUCTION

The renewable energy sources are divided into two main categories: biomass process and water splitting process, also commonly known as water electrolysis. The production of hydrogen through biomass is possible using thermochemical, biological, and electrochemical processes. The biomass used can be derived from agricultural or marine residues, forest byproducts, among others, and its conversion coupled with systems with carbon capture has negative carbon dioxide emissions when compared with processes of reforming fossil fuels, reducing the total greenhouse gas emissions associated to this process (Lepage et al., 2021). The water electrolysis process, using the energy from photovoltaic panels or wind turbines has very low direct carbon-dioxide emissions associated compared to traditional fossil fuels, being considered a green technology. Also, these renewable energies are expanding and becoming more common, and it is expected that by 2030 the market share of solar panels and wind in total electricity generation is of 40%, and by 2050 of 68% (IEA, 2021b) becoming particularly relevant the analysis of this hydrogen production technology.

2.2.1. Water electrolysis technologies

The water electrolysis process consists in separating the two atoms of hydrogen from the one of oxygen present in the water through the application of electricity (Figure 2.2). The necessary electrical power source is connected to two electrodes (or plates) made of an inert metal: anode and cathode. Two main reactions happen in these electrodes: the hydrogen evolution reaction (HER) in the cathode where water is reduced to the produce hydrogen, and the oxygen evolution reaction (OER) in the anode where the water is oxidized to produce oxygen (Wang et al., 2021). In between these two plates there is a membrane, to avoid the contact of these two reactions, stopping the two elements to be recombined in the water. Alongside with membrane, there is the catalyst layer, that speeds up or enables each reaction in both sides.

Several different water electrolysis technologies are named based on the electrolyte or type of membrane used, such as, alkaline water electrolysis, solid oxide electrolysis, Proton Exchange Membrane (PEM) water electrolysis, and Anion Exchange Membrane (AEM) water electrolysis. There is also the microbial electrolysis technology, that uses organic matter to generate electrons and protons. The efficiency of this process is usually determined by the amount of hydrogen produced compared to the heat and energy spent during the process, which translates to the heat and energy lost during the process. The general water electrolysis process has an efficiency that varies between 60% and 82%.

All these technologies present advantages and disadvantages, when it comes to stability, density, efficiency, and production cost. However, as presented by Shiva Kumar & Lim (2022), although alkaline and PEM water electrolysis need some improvements, both processes are scalable, stable and have a higher proven durability than the other technologies, such as AEM and solid oxide electrolysis. Also, PEM presents more favourable conditions than alkaline, since cross-over of gases isn't an issue, its intermittent use can be handled, and has a high operating density but its usual catalysts are made from more expensive materials.

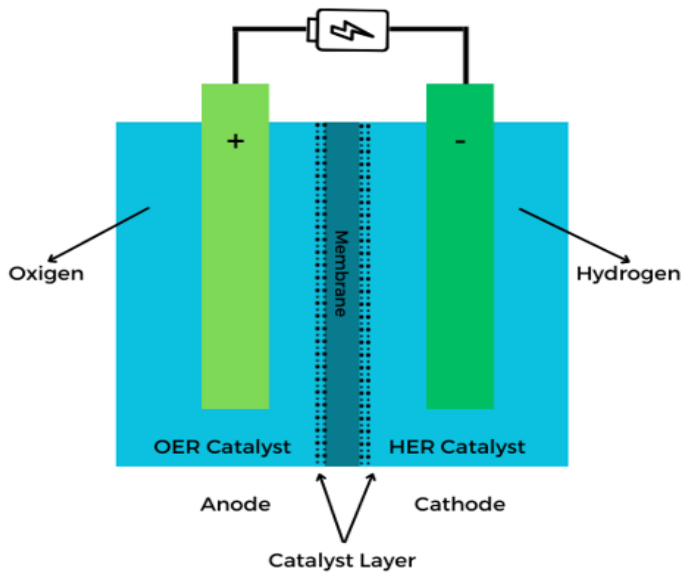

Figure 2.2 – Water electrolysis process sheme

- Alkaline water electrolysis

Alkaline water electrolysis is a known and well stablished technology used in green hydrogen production that has been studied for more than one century, being able to function in large-scale applications. However, it presents as cons the limited current density and the crossover of gases, decreasing the hydrogen purity. Since most catalysts are made from platinum (Pt), the need for lower cost and more available materials for large-scale applications is necessary. Therefore, inexpensive metals have been employed to act as catalysts in this process. As pointed out by Zhang et al. (2023), the use of catalysts based on Nickel (Ni) in substitution of rare materials performed well, but the lack of mechanical stability of the catalyst and hydrogen impureness prevails. It is important to refer that this method doesn't handle well the frequent start-up and shutdown of the technology, because since it operates with high temperature, when it is shutdown, it can provoke a reverse current, damaging the electrodes (Abdel Haleem et al., 2022). This presents as a powerful disadvantage when the technology is coupled with renewable energy power plants, since it is mainly turned on in the moments of energy surplus. Nevertheless, Kojima et al. (2023) present some advanced procedures to deal with the power fluctuations so that this technology can last longer.

- PEM water electrolysis

PEM water electrolysis presents itself as a technology with a considerable operation flexibility, since it has the advantage of handling a large pressure difference, making it a safe process. Also, it does not have electrolyte corrosion and water acts as reactant and cooling medium. This technology can be used directly in power plants, by producing hydrogen, and storing it to act as a cooler, as pointed out before (Xue et al., 2021). However, Bautkinova et al. (2023) points out that there is research to perform in the use of titanium in the porous transport layer, due to the decrease of efficiency of the process caused by the ohmic resistance created in the catalyst layer. In this technology the porous transport layer is situated after the catalyst layer and helps with the transport of electrons, water, hydrogen, and oxygen between the anode and cathode allowing electrochemical reactions to happen. Also, a wind-solar-hydrogen multi-energy supply system using the proton exchange membrane technology has been studied, where it concentrates simultaneously the production of wind and photovoltaic power with the hydrogen production using the power surplus, increasing the energy utilization rate and efficiency of each system component, and increasing the carbon dioxide mitigation (Liu et al., 2023). Results showed that almost half of the energy generated was considered abandoned and then used for the production of hydrogen.

- AEM water electrolysis

Anion Exchange Membrane water electrolysis is a technology in an early stage of research, presenting some advantages and disadvantages. AEM is considered a low-cost technology, since it uses non-noble metals in the catalysts, has noncorrosive electrolyte, and can operate in a high pressure, but it has a low durability, since the membrane can degrade rapidly, and has low conductivity compared to the proton exchange membrane conductivity, therefore this technology still faces some challenges to improve the hydrogen production (Vincent & Bessarabov, 2018).

- Solid oxide electrolysis

This method uses a solid oxide ceramic electrolyte to convert electrical energy into chemical energy, operating in such high temperatures that uses water in form of steam, commonly it uses yttria stabilized zirconia as catalyst, since it has high conductivity and stability in high temperatures. Also, the high temperature can decrease the power consumption during the process, possibly decreasing the hydrogen cost (Seitz et al., 2017). However, the short-term and long-term degradation of both oxygen and fuel electrodes, as well as of the bipolar plates and seals, can put at stake the viability of this technology to be used and implemented in hydrogen system applications (Laguna-Bercero, 2012). Although still in an early stage of research and with some challenges remaining, Nechache & Hody (2021) present some innovative alternatives in order to reduce the degradation of materials, such as using strontium-magnesium doped lanthanum gallate and gadolinium-doped ceria as electrodes.

- Microbial electrolysis

Microbial electrolysis consists of applying electricity in organic matter, including wastewater, to produce hydrogen. Since this technology commonly uses platinum as electrocatalyst, the cost of production is high. There is also the possibility to use a microorganism to catalyse the reaction of electrons and protons to form hydrogen, therefore avoiding the use of a rare metal. Microbial electrolysis presents other disadvantages, such as: the technology needs to be more scalable, since it is still in research and development phase, and the high cost of the use of a membrane in the anode and cathode chambers to separate the hydrogen production from the carbon dioxide produced during the process. There also the possibility of using a membrane-free technology to reduce the cost, but with the trade-off of having carbon dioxide and methane mixed with the hydrogen produced (Kadier et al., 2016).

- Electrolyser materials

Both alkaline water electrolysis and solid oxide electrolysis use platinum-based electrocatalysts in their reactions, which is a rare metal. Due to the lack of availability, nickel was found as a substitute since its performance can be similar to platinum and is abundant and cheaper (Zhou et al., 2020). Although the economical side of the process beneficiates from this substitution, the life cycle of this mineral has some environmental concerns. The greenhouse gas emissions is high, provoked by the high consumption of energy and fossil fuels during the extraction and refining process, independently of the type of nickel (nickel metal, nickel oxide, ferronickel, and nickel pig iron) (Wei et al., 2020). Nevertheless, when compared to precious metals as platinum or palladium, the environmental burdens are smaller (Nuss & Eckelman, 2014). Also, the substitution of other metals by nickel can trigger a significant demand of the commercialization of this material, possibly rising its cost and slowing down the implementation of water electrolysis, if the production does not match the demand (Seck et al., 2023). Shiva Kumar & Himabindu (2019) also point out that it is necessary to find substitutes to electrocatalysts made from platinum in the PEM water electrolysis, referring studies that molybdenum disulfide and palladium should be considered, since they perform similarly. Palladium can be an option since its more abundant than Platinum and therefore more cost-effective.

Ni also has an advantage, like other transition metals as Iron and Copper, that is being present in common waste produced in our society. By using this waste, like electronic waste, to extract the contained metals, it is possible to prepare the catalysts to act in the OER and in the HER, making the process of obtaining hydrogen cleaner (Chen et al., 2023). As mentioned by (Sharma et al., 2021), when referring specifically to electronic waste, "E-waste is predicted to double by 2045", making waste-derived catalysts extremely relevant. It not only contributes to achieving the NZE, as it contributes to the circular economy and waste management. In addition, it is also possible to obtain Ni from the recycling of batteries used on electric vehicles, therefore reducing its environmental footprint, and improving circularity, but the weight of the recycled Ni obtained compared to the need of energy and water used during the nickel extraction and refining process is still very small (Golroudbary et al., 2023).

2.3. International Representation

Although, until the end of 2022, the world relied heavily on fossil fuels to meet its energy needs, especially in the emerging countries, registering a growth between 2000 and 2021 as a primarily energy supply, in the first world countries, this consumption source dropped in the same period (IEA, 2023). In addition, in 2022, the investment in clean energy technology surpassed USD 1.4 trillion, increasing in 10% compared to 2021, and 70% of the growth in the energy sector in that year was attributed to investments in clean energy. This behaviour did not happen spontaneously, it was provoked by the climate and energy crisis and by the creation of the worldwide agreement in 2015, Paris Agreement (UN, 2015). This international convention triggered the creation of several roadmaps throughout the world, such as the NZE Scenario from IEA (2021b). It is possible to see in Figure 2.3 the governments' concern rising throughout the time in finding ways to fight against the energy crisis. Not all roadmaps focus specifically on Green Hydrogen, most of them refer using hydrogen independently of its source, but all expect to use hydrogen in a daily basis as an energy vector in the future, even if it considered green or not. Nevertheless, the European Green Deal focuses on renewable energy produced hydrogen (IRENA, 2022).

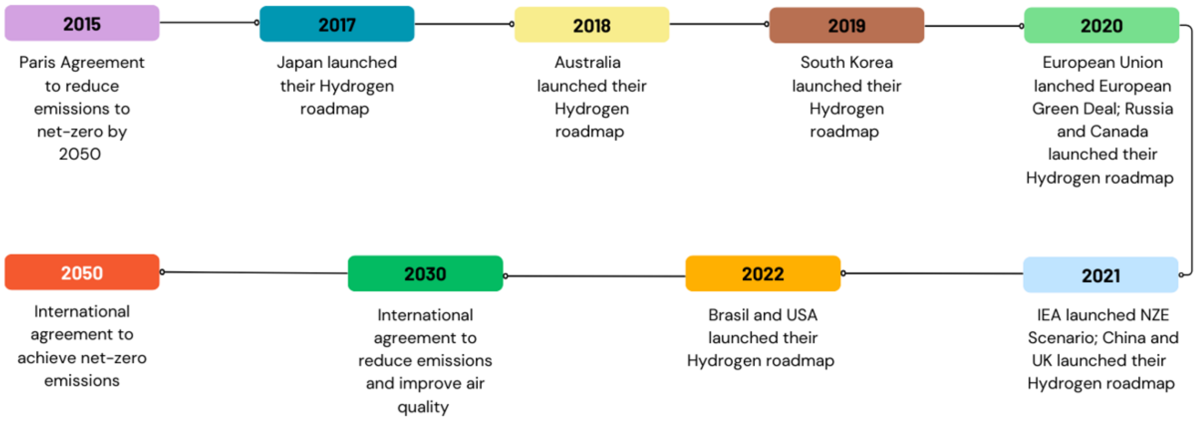

Figure 2.3 – Hydrogen roadmap world evolution

The European Union (EU) created a roadmap with the deadline in 2050 focused on clean energy. In 2020, the EU adopted a strategy to put into action a hydrogen ecosystem, promoting the research in this matter as well as creating infrastructure to achieve a climate-neutral Europe. Inside this roadmap the European commission created the European Green Deal to strive to be the first continent to become climate neutral, establishing two main objectives: achieving the NZE by 2050 and reducing the greenhouse gases by at least 55% by 2030, compared to 1990 levels. Although this initiative focuses not only on climate policies but also in social matters, green hydrogen has a key role in it. Alongside with this initiative, it was also created the European Clean Hydrogen Alliance, to bring together the industry, mobility sectors and others to a common goal. The EU cohesion policy, under the Just Transition Fund, is creating plans to assist governments facing the socio-economic challenges associated with the transition towards a climate neutral economy.

The NZE Scenario by IEA shows that by 2050, the renewables will be a stronger production source than the conventional fossil fuel energy, having heavy increase starting in 2030. Also, the scenario indicates that hydrogen will have a 10% share of total final energy consumption by 2050, being used mainly in heavy industry and long-distance transport.

Therefore, the demand for projects and initiatives to put green hydrogen into our economy has been rising. As said in the *Global Hydrogen Flows* report by the Hydrogen Council together with McKinsey & Company (2022), China, India, Japan, South Korea, Europe, and North America have been flagged to be accountable for 75% of the global hydrogen demand by 2050, but there is a geographical mismatch of the demand centres versus the productions centres when it comes to price and capacity. Therefore, they identify three groups that share the same characteristics: countries with high hydrogen-export potential due to their competitive price per kilogram of hydrogen like middle East, south America, and southern Africa; countries with both cheap supply and large demand, like China and North America; and demand locations where cheap supply is limited or not available, like Europe, Japan, and South Korea. In 2017, North America, had already 35 hydrogen public stations and 27 private stations to provide fuel for vehicles, mostly using hydrogen obtained from steam reforming (Kurtz et al., 2019). In 2019, Asia had more than 200 hydrogen refuelling stations, and Europe had 185, 44% of which in Germany (Genovese et al., 2023).

Brazil is also considered a potential strong producer of green hydrogen since their production of renewable energy, especially hydroelectric energy, is already their cheapest source and their energy internal market is well stablished (Kelman et al., 2020). In addition, the Economics Institute of the Rio de Janeiro Federal University created the Study Group on the Electric Energy Sector (GESEL) to promote the research on electric energy in Brazil. Now a days, this group is extremely active in regulation, economy, electric integration, and innovation around this subject. Furthermore, this group launches frequently an informative report containing insightful information of the activity in subjects related to green hydrogen of Brazil and other countries, such as, politics and funding, production, storage and transportation, final consumption, technology and innovation, events, and articles and scientific studies.

Using a hydrogen-related patent analysis, the World Intellectual Property Organization (WIPO, 2017) concluded that United States and Japan are leading this advance, when it comes to searching for hydrogen production, hydrogen storage and hydrogen fuel station (Sinigaglia et al., 2019), which corresponds to the predicted demand mentioned above. However, the patents publications on the subject have been decreasing throughout the last years.

By analysing the critical technology tracker, a think tank created by the Australian Strategic Policy Institute (ASPI, 2023) (consulted on 14th November 2023), in the topic "Hydrogen and ammonia for power", the United States and Japan, among others, lost their position to China. This conclusion is taken taking into consideration the research contribution of each country with the countries ranked by the highest H-index – a performance metric that analyses the impact of an article based on the citation number – and by the proportion of articles that are in the top 10% most highly cited. China is by far the leader in both rankings.

2.4. Portuguese Hydrogen Investment

In 2015, after the Paris Agreement, produced and approved in COP21, Portugal assumed the challenge to achieve NZE by 2050. Since Portugal belongs to EU, its strategy is also aligned with European Green Deal. To achieve such milestone, Portugal created two roadmaps: Roadmap for Carbon Neutrality 2050 and National Energy and Climate Plan 2021-2030 (PNEC 2030), and created as well a national strategy specific for hydrogen (National Hydrogen Strategy), with the objectives aligned with the two mentioned roadmaps.

In 2018, Portugal was the sixth country in the EU with the highest level of incorporation of renewable energy, having a share of renewable energy in the gross final energy consumption of 30%, which makes the country particularly competitive for green hydrogen production. Furthermore, Portugal has a high potential to lower its greenhouse emissions through renewable energy, such as photovoltaic, solar, wind, hydroelectric, and geothermic. Portugal expects to start a project in industrial scale in Sines to produce green hydrogen by using the existing renewable sources and distribute it first nationally and then, distributing it in an international scale, since it gathers excellent conditions, as being a port of deep waters next to the Atlantic coast, has the available transport and storage infrastructure, and has the possibility to connect to the existing transport network of natural gas (Ministério do Ambiente e da Ação Climática, 2020). However, as pointed out by Khatiwada et al. (2022), the infrastructure will need some refurbishment to make the transition to hydrogen, which will rise the cost of hydrogen production and utilization, at least in the first phases. Additionally, in recent years the EU mobilized 223€ million for Portugal to shut down successfully the three main responsible CO_2-emitting plants of the country.

3. METHODOLOGY

For this dissertation, scientometric data to study the Green Hydrogen breakout was collected. This data consists of scientific publications and related content materials, in order to analyse the progression made in the field of Green Hydrogen. The collection includes scientific production from academic institutions, investigation centres and companies. Although usually investigation outpaces industry and market application, with this study it is possible to identify current research areas, as well as areas where further investigation is needed. Furthermore, since the analysis also focuses on production methods, it is possible to gather insights into the specific areas of interest within the scientific community.

Figure 3.1 shows the flow diagram from the data collection until the analysis made in this dissertation. The collection comprises articles that contain the term "green hydrogen" in the title, keywords or abstract, constituting in 1673 collected articles. The thematic can be considered recent, since the first article appeared in Web of Science (WoS) in 1997. The collected data is shown starting in that year. The dataset was obtained on May 29th, 2023, and to ensure complete years, the dataset only shows articles until the end of 2022, so that was the only timespan restriction. The dataset came from 453 journals and was authored by 5354 individuals, with 4064 author's keywords.

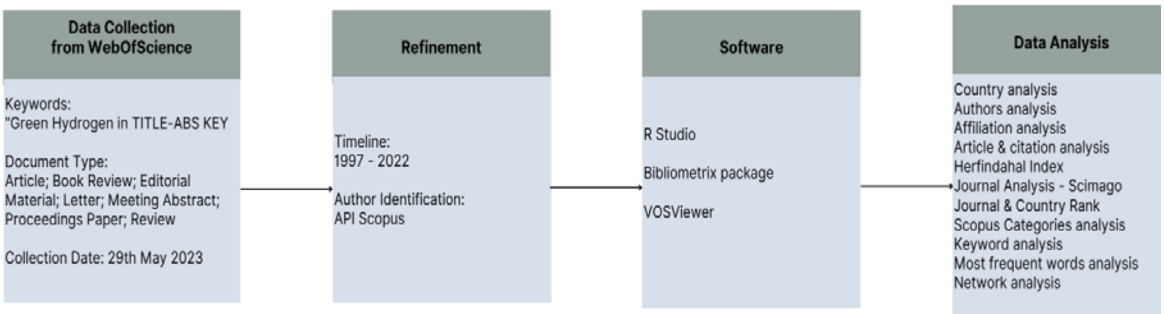

Figure 3.1 – Research Design

Similar to the research design from Mendonça et al. (2022), summary statistics, descriptive analyses, and network analyses were conducted based on the publication records to understand where the knowledge production of this thematic is placed. The dataset used for this purpose was collected from the Web of Science database and, by using an API to connect to Scopus database, we obtained the author identification. The process of author disambiguation was performed using an R package called "Bibliometrix" which retrieved the authors' unique identifiers and affiliation dates. Journal ranking positions were obtained from Scimago, a public portal that contains the journals influence indications, using the information from Scopus database.

These records were processed to obtain descriptive analysis, such as count data, aggregations, averages, proportions, and growth evolution. The Herfindahl Index, an economic measure, was used to measure the number of countries contributing to the subject per year – the lower the value, the more "competition" exists because more agents are investing in the same matter. In this scenario, a lower value is preferable because more countries are contributing to the growth of scientific production. A compact classification of the extracted Scopus categories was also performed, to analyse the evolution of these categories in higher level, rather than in an article-by-article perspective.

Network analysis was also performed, with the output of graph representation and general metrics, such as, closeness, degree, and betweenness. Closeness measures the average shortest distance from each node to any other node, degree calculates the number of paths (edges) a certain node has to other nodes, and betweenness is measured by the number of shortest paths between two nodes that pass through a third node. The visualization tool used for the networks was VOSViewer, that has its own clustering technique. This technology allows the manipulation of clusters, such as, the possibility to define the minimum size of clusters in the network built by VOSViewer and the option to merge small clusters. In this scenario, the association strength method was used to normalize the strength of the links between items. In VOSViewer, an item only belongs to one cluster and the clusters do not need to exhaustively cover all items in a map which can lead to the existence of items that do not belong to any cluster. Also, the bigger the bubble in the network, the more connections it has.

Additionally, business topic evolution analysis was conducted, taking into consideration the topics: Renewable Energy, Sustainability, Transport, Storage, and Hydrogen Economy. The search for these topics was made in the title, abstract, and keywords.

An auxiliar quantitative analysis was also made for the term "water electrolysis" to compare with behaviour of the green hydrogen research. Since these two terms are directly associated, this comparison was made to confirm if the growth of articles published referring to "green hydrogen" was a sign of increasing interest in the research or a progressive vulgarization of the term. The process was the same – the dataset extraction was done in the Scopus database, in the same period of time, obtaining 7869 articles. After the API call, the final dataset was composed by 7681 articles. Although the first appearance of this term in the database was in 1916, we filtered out the dataset to make the comparison with the same timeline.

4. RESULTS AND DISCUSSION

4.1. GENERAL ANALYSIS

Since green hydrogen as an energy source is a recent term compared to hydrogen or water electrolysis, we considered the whole timespan extracted from our data source. The first article was published in 1997, and until 2005, there wasn't significant interest in this theme. From 2016, the interest in the thematic starts rising, but in the last two years we noticed a significant increase of scientific publications on green hydrogen – in recent years the publication number more than doubles year on year, having an exponential growth (Figure 4.1). A linear regression model was used to understand the growth foreseen. This evolution was higher than the calculated, as it is possible to observe when comparing the black line with the actual collected values with the dashed blue line calculated in the linear regression model. The adjusted R-square has a value of 0.8759, showing the reasonable adjustment of the model to the given data.

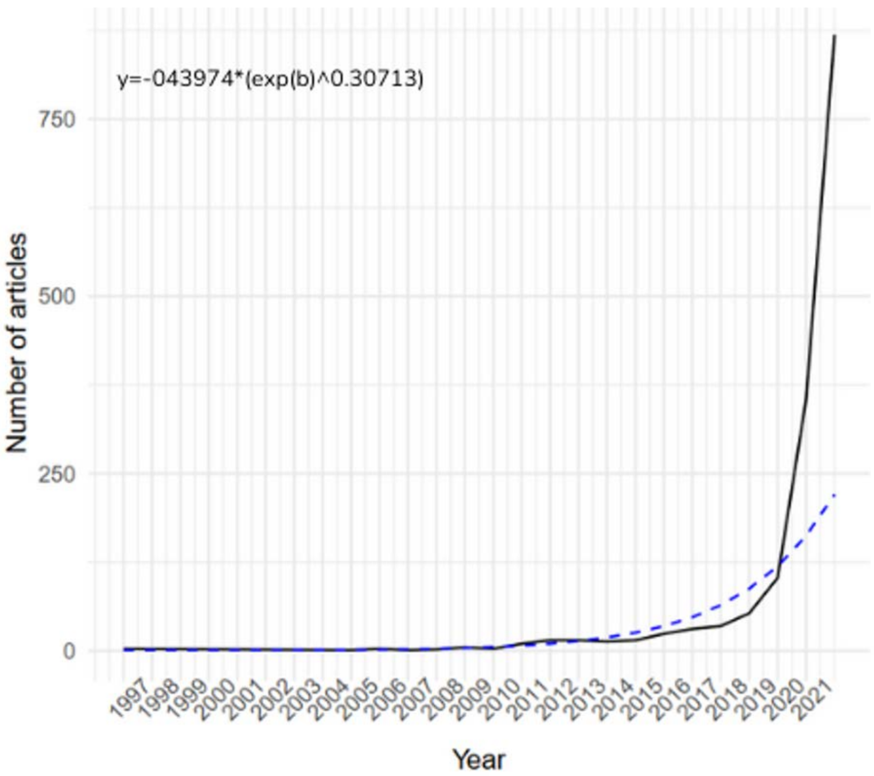

Figure 4.1 – Research items items published on Green Hydrogen from 1997 to 2022

A similar trend was observed in the publications that mention water electrolysis, as seen in Figure 4.2, justifying the growth of published articles in green hydrogen production due to the rising interest in this research area and in green technology and showing the quality of the analysis. A linear regression model was also applied, and its shows how exponential the growth of this technology is. The adjusted R-square is 0.9261, showing that the model is well adjusted to the data.

By analysing the demographics of knowledge production, China is the country that published more items, followed by Germany, South Korea, USA, and Japan (Figure 4.3). As mentioned before, the EU has invested to achieve the NZE scenario, creating the European Green Deal in 2020, and the effort of the European countries can be seen in the top 20, highlighting Portugal with 31 articles published. In addition, the emerging economies are producing some knowledge as well, like India, Saudi Arabia, Egypt, Brazil, and Turkey.

Taking a closer look to the top 5 countries when it comes to number of articles published, they all had a significant increase after 2020, except for Japan (Figure 4.4). This figure enhances the growth of China, from having approximately 20 articles published in 2020 to 250 articles published in 2022.

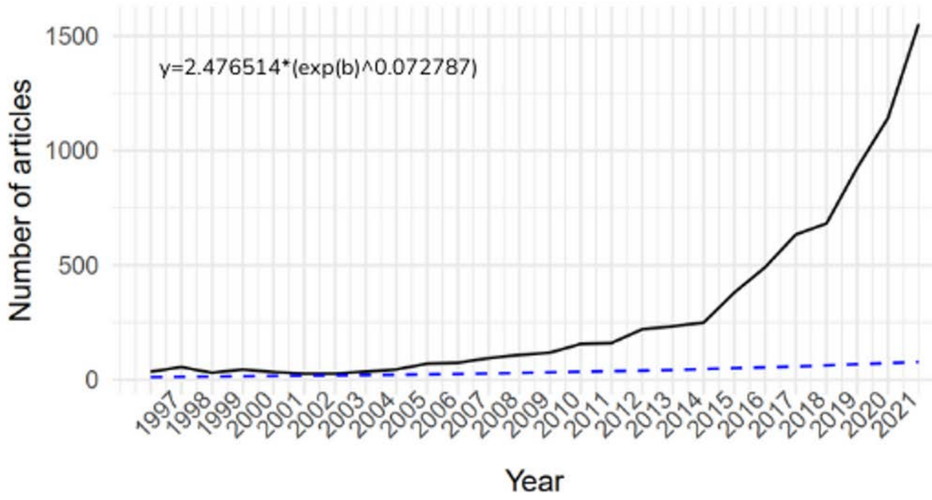

Figure 4.2 – Research items published on Water Electrolysis from 1997 to 2022

When it comes to first author articles per one million habitants, taking into consideration the countries' populations in 2020, the European countries have a very positive performance. Comparing the top 5 countries by number of articles, South Korea and Germany are the only ones in the top 5 of first author articles per 1M habitants. Interestingly, Portugal appears at the top of this list, having 2.53 first authors articles per million of habitants, showing the interest and productivity of authors affiliated to Portuguese institutions in this thematic. Mentioning again the authors from emerging economies, Saudi Arabia, Turkey, Egypt, Brazil, and India are also contributing to the matter, even if in a smaller scale (Figure 4.5).

Analysing the citations by author of a given country, i.e., the country of the institution which the author is affiliated to, China is by far the country with most citations, having 2.5x more citations than the second country (Figure 4.6). Analysing the geography, the most relevant countries in terms of citations are predominately Asian, whereas the most relevant countries in terms of published are mainly European.

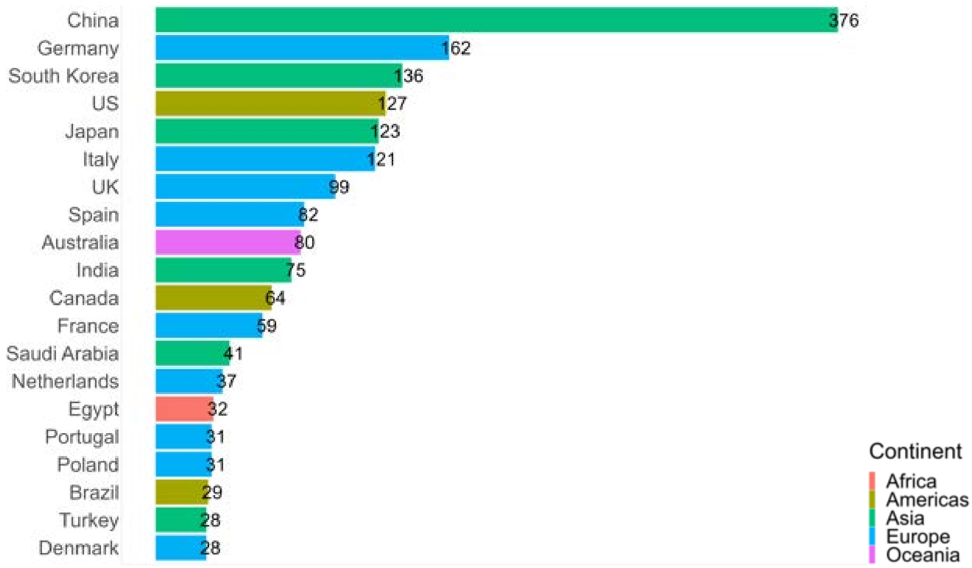

Figure 4.3 – Top 20 countries per number of articles published

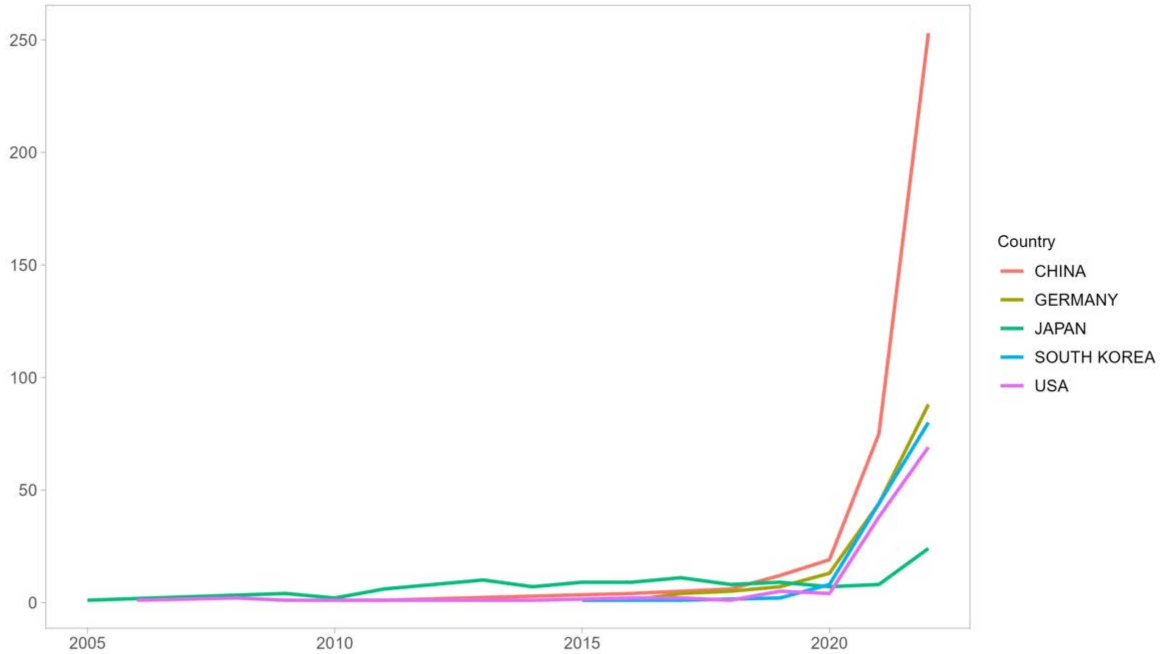

Figure 4.4 – Number of articles published per year per top 5 countries

Taking a closer look to Portugal, the top 10 Portuguese most recently affiliated authors are mostly affiliated to the International Iberian Nanotechnology Laboratory, a Spanish-Portuguese investigation centre in Braga, Portugal, and to the Universidade do Porto. The International Iberian Nanotechnology Laboratory has in total 336 citations and 19 published articles, the Universidade do Porto has 144 citations and 14 published articles, and the Universidade do Minho has 33 citations and 1 published article (Table 4.1).

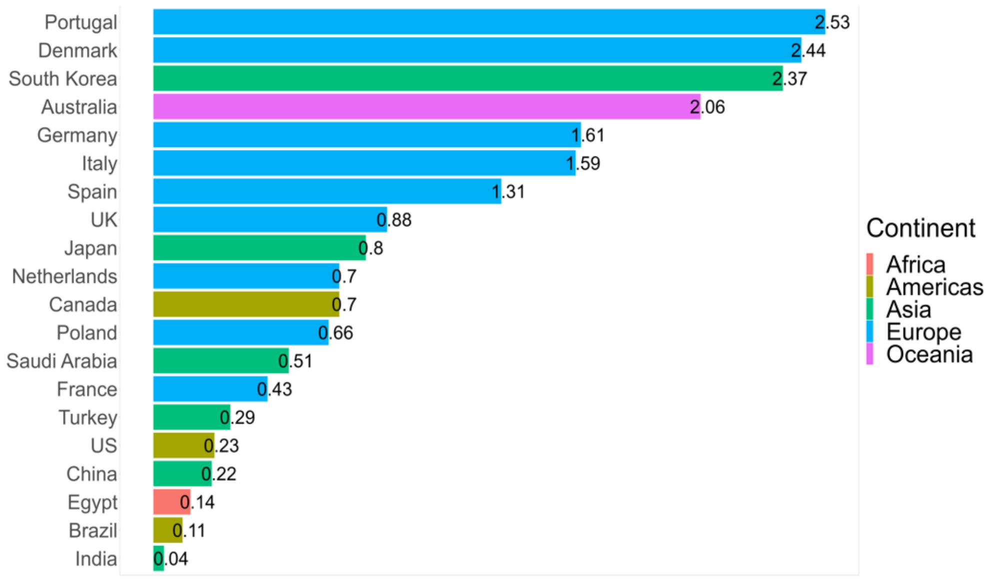

Figure 4.5 – Top 20 first author articles per 1M habitants

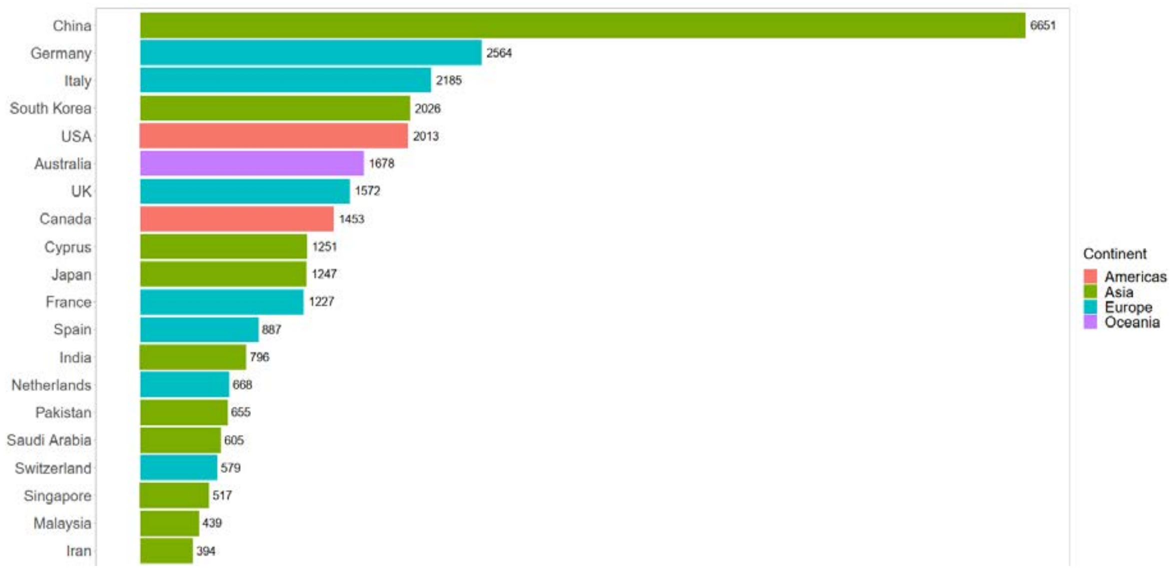

Figure 4.6 – Top 20 citations by author of a given country

Analysing the top 5 countries with most citations (Figure 4.7), the pattern is not the continuous growth after 2016, with an acceleration starting in 2020, as we have seen before when it comes to publications, but a few ups and downs specially after 2015. China presents a slow growth between 2011 and 2017, from 2017 to 2018 increases around 500 citations, in the next year decreases around 400 citations, and starting in 2019 China presented an elevated growth until 2022 with more than 2000 citations. Germany was up and down from 2016 until 2019 with around 300 citations and from 2019 to 2021 increased around 500 citations. From 2010 to 2019, Italy had few citations, but from 2019 to 2021, the citation number grew more than 600. South Korea started with around 100 citations in 2015, in 2019 reached around 600 citations, but in 2020 lowered to 200. In 2021, this country grows to 700 citations. USA is the country that started having citations before the others but didn't have a significant growth until 2020. From 2020 to 2021, the United States increased more than 700 citations. After

2021, Italy, South Korea, and USA, decreased in around 200 citations and Germany had a light decrease.

Table 4.1 – Top 10 Portuguese affiliated authors with most articles

Index Name	Affiliation	Number of Citations	Number of articles
Liu L.	International Iberian Nanotechnology Laboratory	85	6
Yu Z.	International Iberian Nanotechnology Laboratory	72	4
Madeira L.M.	Universidade do Porto	65	7
Amorim I.	International Iberian Nanotechnology Laboratory	58	4
Soria M.A.	Universidade do Porto	57	5
Araujo A.	International Iberian Nanotechnology Laboratory	55	3
Zhang N.	International Iberian Nanotechnology Laboratory	33	1
Bento F.	Universidade do Minho	33	1
Xu J.	International Iberian Nanotechnology Laboratory	33	1
Faria J. L.	Universidade do Porto	22	2

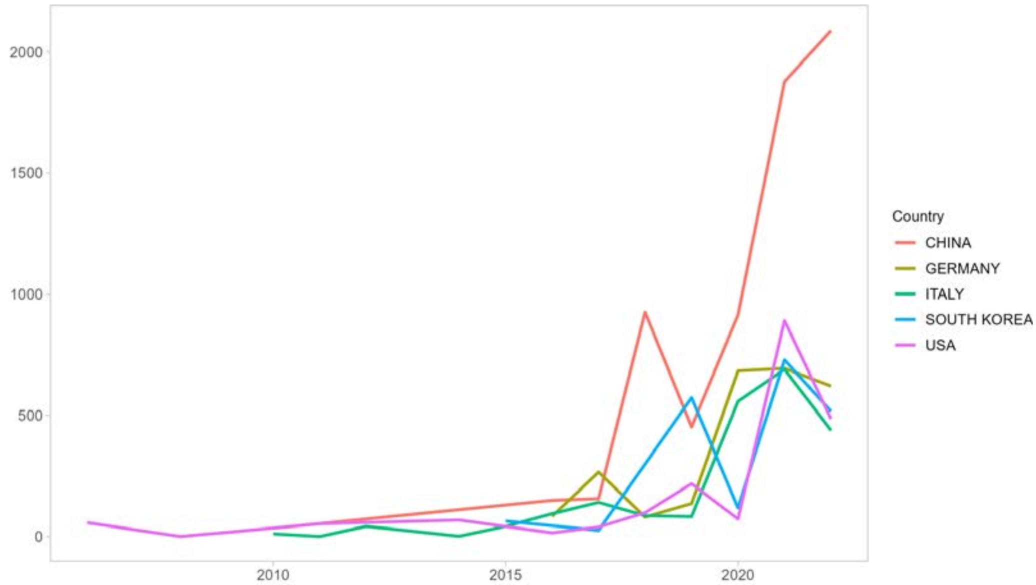

Figure 4.7 – Top 5 countries with most citations per year

The Figure 4.8 shows how the green hydrogen thematic spreads throughout the years. Since 2016, the number of countries publishing in this area starts growing, having a similar behaviour as the evolution of published articles. It is important to notice that the number of countries increased significantly, going from 8 countries participating in 2012 to nearly 80 in 2022. The Herfindahl Index (Figure 4.9) enhances this ascending movement, highlighting that the green hydrogen related articles are becoming more distributed between different countries, having a significant drop between 2008 and 2010, from the maximum value to 3333, and between 2015 and 2016, from 4133 to 1840. Analysing both figures it is possible to see that more countries are becoming interested in Green Hydrogen and innovating in this area. However, when applied the linear regression model in Figure

4.8, with an adjusted R-square of 0.8759, it is possible to see the country growth evolution wasn't as high as predicted.

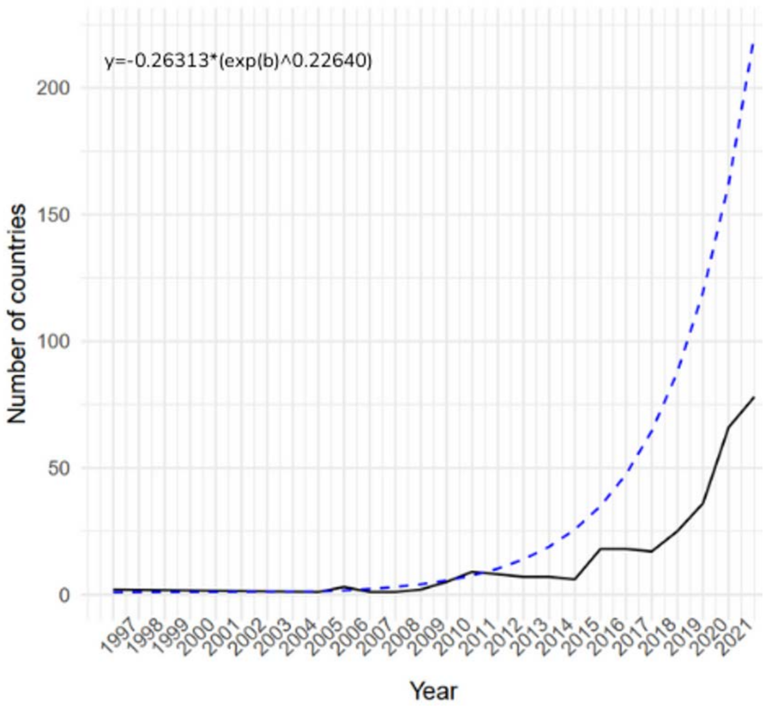

Figure 4.8 – Number of countries participating for Green Hydrogen related articles from 1997 to 2022

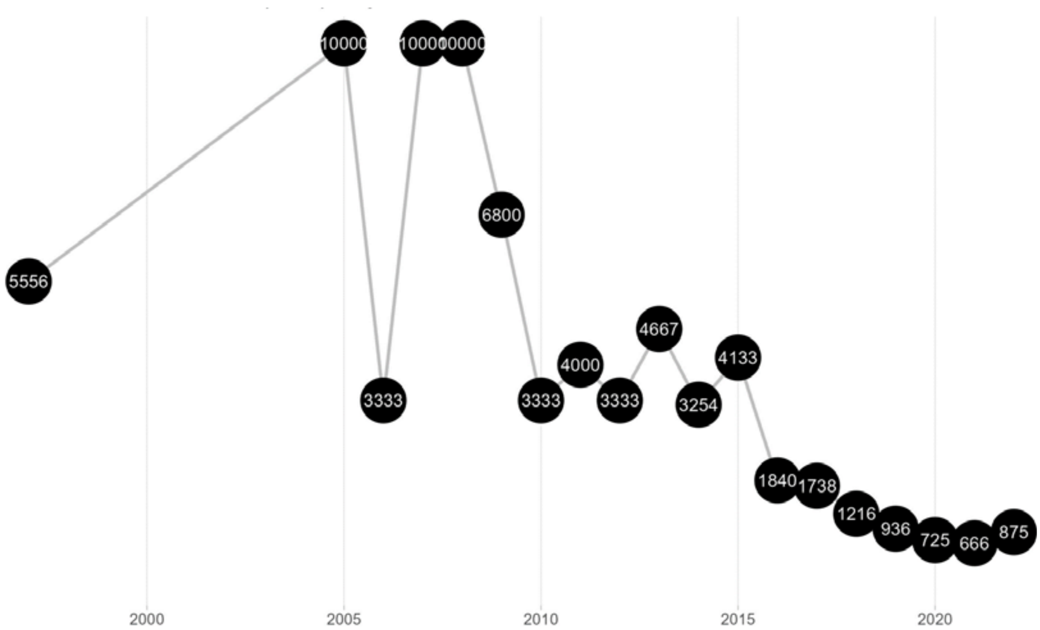

Figure 4.9 – Herfindahl index for countries participating in Green Hydrogen related articles

When it comes to research players, Yokohama National University in Japan, is the institution with more published articles, having three times more publications than the second research player, contributing to put Japan in the top 5 countries that have more articles. However, the total number of citations shows a different perspective, since the articles with citations are affiliated to a Cyprus

University. A Portuguese university, Universidade do Porto, appears as the fifth institution with more articles published in this dataset, putting the Portuguese scientific community in the map. In this analysis there was not a distinction between academic and non-academic institutions, since the majority relevant non-academic institutions in terms of article number and citation number are research centres and laboratories and the investigators of those institutions are also usually associated to universities. Nevertheless, Nissan Arc, Ltd, a private company, is in second position in the top 20 number of articles with 23 articles published, showing great interest from this car manufacture company in the green hydrogen thematic (Figure 4.10).

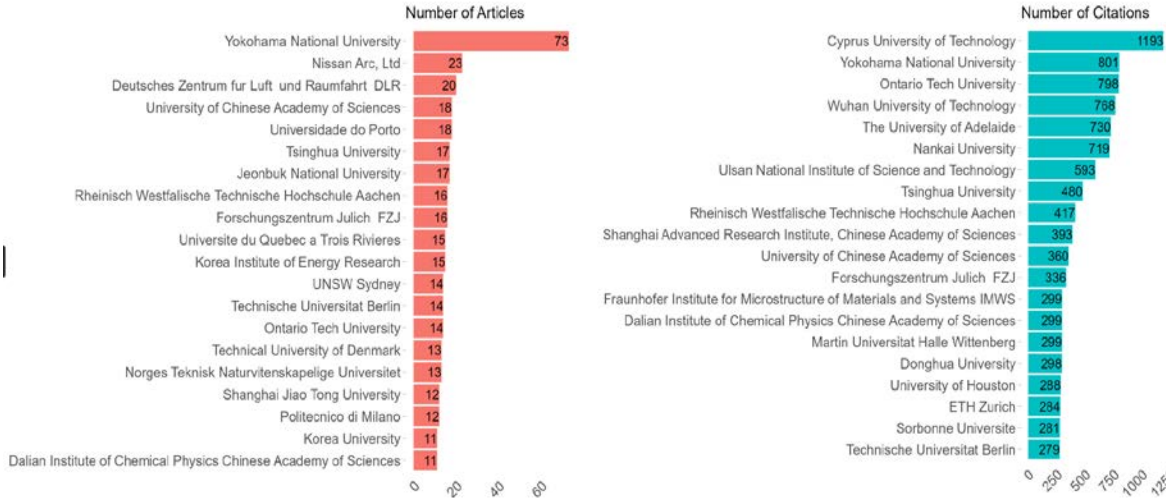

Figure 4.10 – Top 20 institutions by number of articles and number of citations

The top 4 journal with most articles published about this thematic are all Energy related (Figure 4.11). According to the Scimago Journal & Country Rank, which is a public portal with scientific indicators developed from data retrieved from Scopus from 1996 that measure the influence and visibility of the journals, all these journals are positioned in Quartile 1 since 2015. [1]

The geography of the 10 most cited articles is represented by a considerable number of European countries but has also the presence of some of the top 5 countries with more articles, like China and South Korea (Table 4.2). These articles, as the dataset suggests, are focused mainly on ways of production, and not on the whole hydrogen economy.

[1] The journals are categorized annually in one of the four quartiles in each research area. Being positioned in the quartile 1 means that a certain journal ranks in the top 25% articles with highest number of citations within a selected year by documents published in the selected journal in the three previous years.

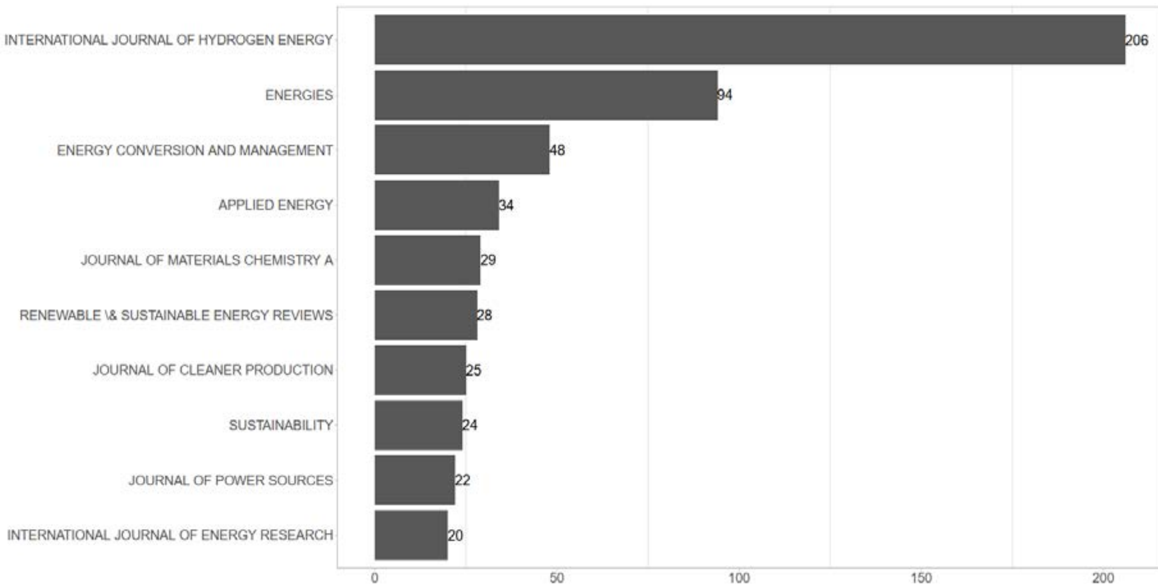

Figure 4.11 – Top 10 Journals per number of green hydrogen related articles

Table 4.2 – Most cited articles

Article	Citations	Year	Authors	Lead Country	Countries	Affiliations
A Comparative Overview Of Hydrogen Production Processes	1189	2017	Nikolaidis P.; Poullikkas A.	Cyprus	Cyprus	Cyprus University of Technology
Metal-Free 2d/2d Phosphorene/G-C3n4 Van Der Waals Heterojunction For Highly Enhanced Visible-Light Photocatalytic H-2 Production	626	2018	Ran J.; Guo W.; Wang H.; Zhu B.; Yu J.; Qiao S.Z.	Australia	Australia; China	The University of Adelaide; Nankai University; Wuhan University of Technology
Green Methods For Hydrogen Production	594	2012	Dincer I.	Canada	Canada	Ontario Tech University
Toward Practical Solar Hydrogen Production - An Artificial Photosynthetic Leaf-To-Farm Challenge	540	2019	Kim J.H.; Hansora D.; Sharma P.; Jang J.W.; Lee J.S.	South Korea	South Korea	Ulsan National Institute of Science and Technology
Bifunctional Heterostructured Transition Metal Phosphides For	298	2020	Zhang H.; Maijenburg A.W.; Li X.;	Germany	Germany; China	Martin Universitat Halle Wittenberg; Donghua

Efficient Electrochemical Water Splitting			Schweizer S.L.; Wehrspohn R.B.			University; Fraunhofer Institute for Microstructure of Materials and Systems IMWS
Green Hydrogen From Anion Exchange Membrane Water Electrolysis: A Review Of Recent Developments In Critical Materials And Operating Conditions	208	2020	Miller H.A.; Bouzek K.; Hnat J.; Loos S.; Bernäcker C.I.; Weißgärber T.; Röntzsch L.; Meier-Haack J.	Italy	Italy; Czech Republic; Germany	Istituto Di Chimica Dei Composti Organometallici, Sesto Fiorentino; University of Chemistry and Technology, Prague; Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM; Leibniz Institut fur Polymerforschung Dresden e V
Water Electrolysers With Closed And Open Electrochemical Systems	184	2020	Lagadec M.F.; Grimaud A.	France	France	College de France; CNRS FR3459; Sorbonne Universite
The Role Of Carbon Capture And Utilization, Carbon Capture And Storage, And Biomass To Enable A Net-Zero-Co2 Emissions Chemical Industry	169	2020	Gabrielli P.; Gazzani M.; Mazzotti M.	Switzerland	Switzerland; Netherlands	ETH Zurich; Copernicus Institute of Sustainable Development
The Role Of New Energy In Carbon Neutral	166	2021	Zou C.; Xiong B.; Xue H.; Zheng D.; Ge Z.; Wang Y.; Jiang l.; Pan S.; Wu S.	China	China	Research Institute of Petroleum Exploration and Development
The Role Of Green And Blue Hydrogen In The Energy	163	2021	Noussan M.; Raimondi	Italy	Italy	Fondazione Eni Enrico Mattei

Transition-A Technological And Geopolitical Perspective	P.P.; Scita R.; Hafner M.	

Although the thematic is related with clean energy, the category group where the analysed papers grew the most (280%) is Natural Sciences and the group with most citations is the Science & Technology, with 20,8 citations in average (Table 4.3). Nevertheless, the Energy category is the one with second best average citation (16,2). The extracted data presents the Scopus categories attributed to each extracted article and these were organized in a more generic classification by aggregating categories to make a more general analysis (Table A 1). In Figure 4.12, it is possible to see each aggregated category graphical evolution. All the groups had an exponential growth starting in 2020, and before that, almost all had few publications (less than twenty per year).

Table 4.3 – Category groups general analysis

Category Group	**# Articles**	**Percentage**	**Avg. Citation**	**Total Citations**	**Avg. Growth**
Exact Sciences	966	59,81%	15,5	14968	65,13%
Energy	802	49,66%	16,2	13003	72,97%
Engineering	433	26,81%	10,3	4468	89,74%
Science & Technology	288	17,83%	20,8	5993	89,25%
Environmental Sciences	117	7,25%	14,6	1709	129,1%
Life Sciences	60	3,72%	11,1	667	233,33%
Natural Sciences	56	3,47%	10,9	611	280,58%
Social Sciences and Humanities	27	1,67%	13,9	375	157,5%

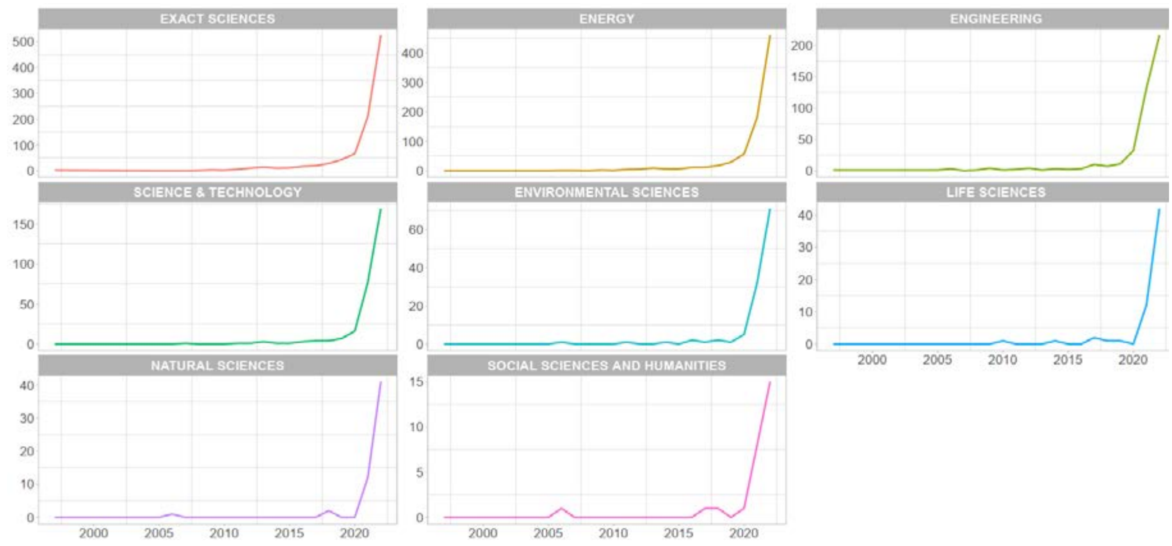

Figure 4.12 – Evolution of the aggregated categories

4.2. Keywords and Most Frequent Words

During this analysis, three different keyword analysis were made: unigrams, bigrams, and trigrams. All these graphics are a way of analysing the relevance of the published keywords overtime, therefore understanding the trends related to this topic. However, by analysing one word isolated, the conclusions are dubious. Taking as example the word “fuel”, it can be related either to the keyword “fuel” or the used term “fuel cell”, both are targeted as the same, even if they refer to different meanings (Figure B 1).

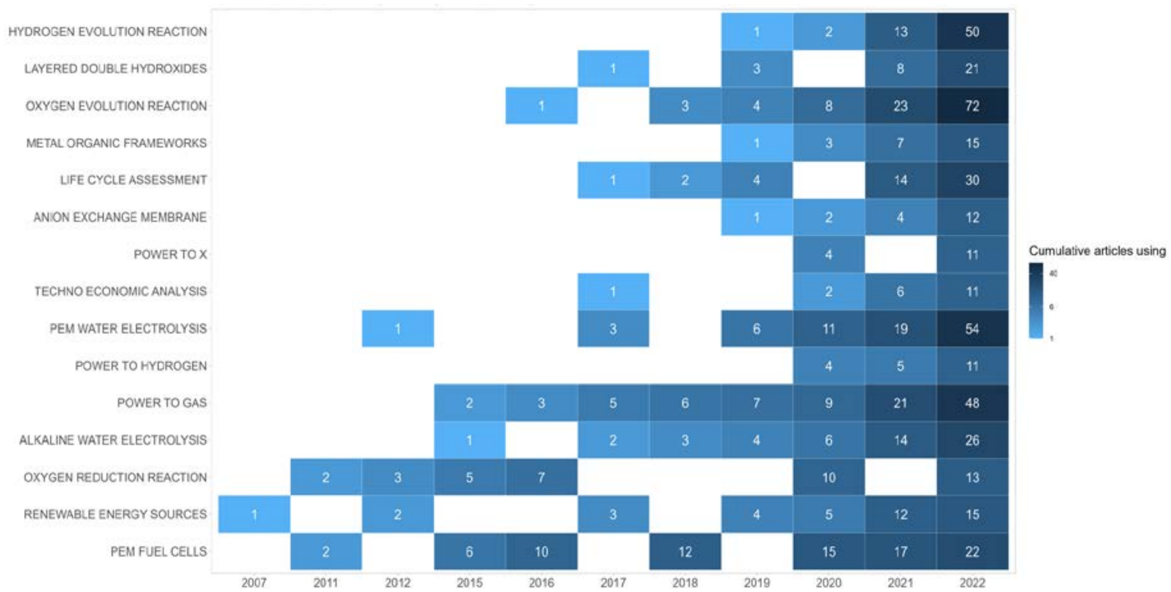

Figure 4.13 – Keywords Trigram

Although the dataset has a relatively small size, since it has less than 2000 observations, and the trigrams narrow the research by referring to very specific terms, having less occurrences and a smaller growth, it is possible to observe some interesting terms starting to come to the surface. The term “PEM Water Electrolysis” had a significant growth in this analysis, highlighting the relevance of this technology. Also, terms that refer to the specific processes, such as “Oxygen Evolution Reaction” and

"Hydrogen Evolution Reaction" are being studied, and gain importance in the last two years, showing the effort to improve in efficiency in the water electrolysis process (Figure 4.13). In the last two years, other technologies show evidence of being studied as well, such as "Anion Exchange Membrane" and "Alkaline Water Electrolysis", but not as much as PEM. The term "Life Cycle Assessment" highlights the importance given to the analysis of the whole cycle of energy production/storage and points to a circular economy perspective. The growth of the term "Power to Gas", that is, the technology that uses electric power to produce a gaseous fuel, shows the relevance of green hydrogen production as a form of renewable electricity storage.

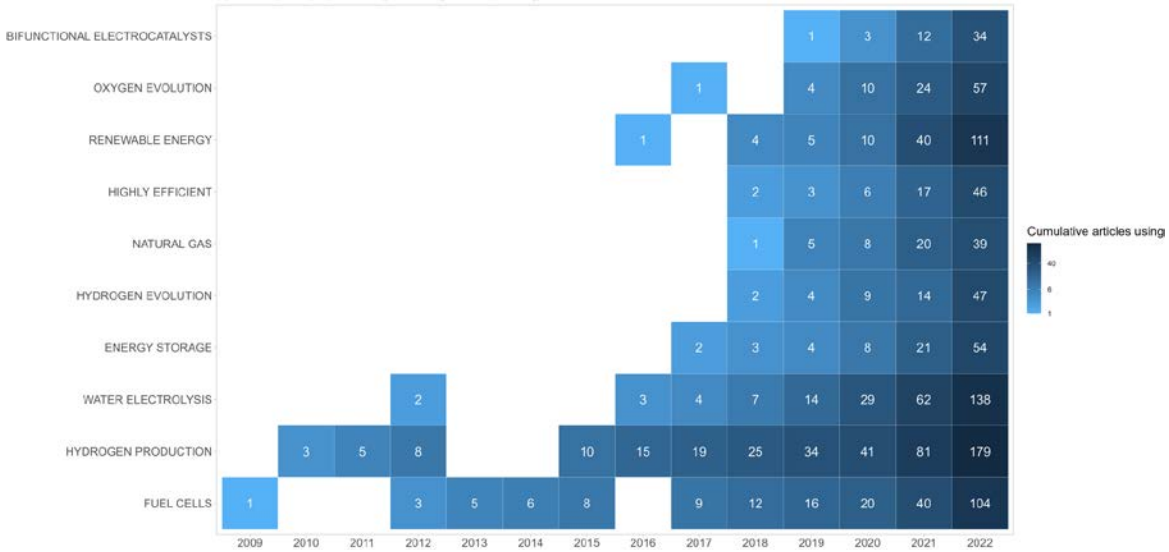

Figure 4.14 – Keywords Bigram

In the bigram (Figure 4.14), "Hydrogen Production" and "Water Electrolysis" are the most used term in all years, showing that the growth of interest in hydrogen production is real. "Renewable Energy" is growing fast as well, which goes along with the theme, since green hydrogen is produced through the surplus of renewable power sources like solar and wind. Fuel cells are proved to be also a topic associated to this thematic, existing since an early stage. The evolution of "Highly Efficient", "Oxygen Evolution" and "Hydrogen Evolution" show the increasing search for improving the efficiency of this technology.

We also analyse in a closer optic the evolution of the terms "PEM Water Electrolysis" and "Alkaline Water Electrolysis" since these two technologies can be promising to produce Green Hydrogen, compared to others, as seen in Section 2.2.1. The Figure 4.15 represents the growth of the terms "Alkaline Water Electrolysis", "Alkaline Electrolysis", and "Alkaline Water Electrolysis System" in the Alkaline curve, and the terms "PEM Water Electrolysis", "PEM", and "PEM Water Electrolysis Cells" in the PEM curve.

Although Alkaline Electrolysis is a more established process and has been studied before PEM started being studied, it cannot work with intermittent power, and PEM Water Electrolysis can be switched on and off without risk, becoming a more adequate technology to store the surplus produced by solar PV and wind energies. The exponential growth of the term PEM suggests the growing interest in the green hydrogen production using the surplus of those two specific energy production technologies (solar PV and wind), especially when compared to the not so fast growth of the alkaline technology.

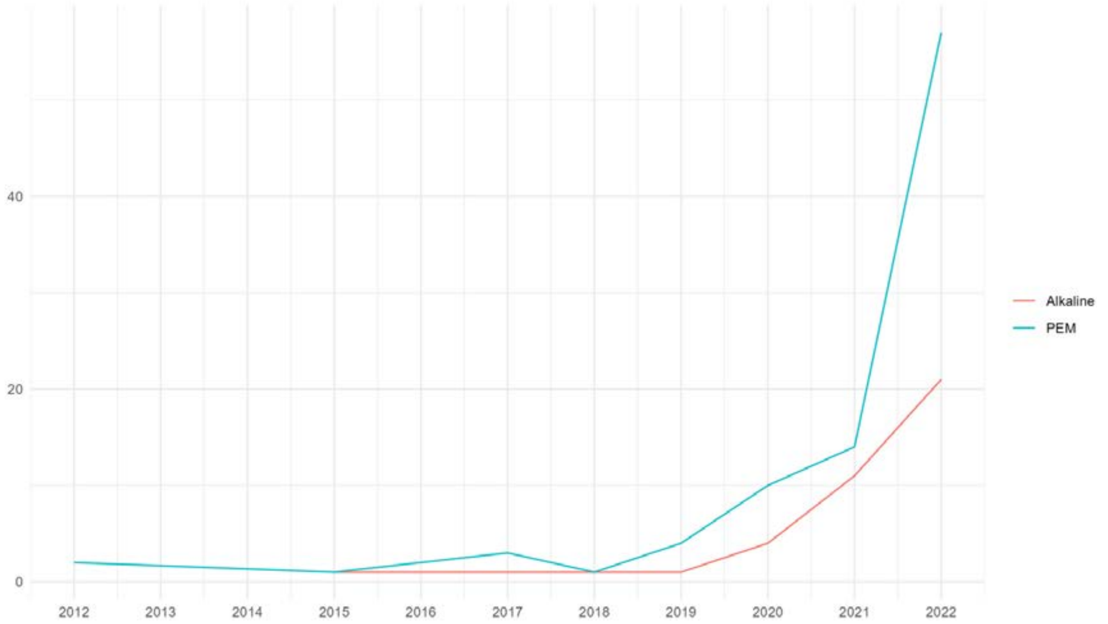

Figure 4.15 – Evolution of Alkaline and PEM water electrolysis

To conduct the most frequent words analysis, it was taken into consideration not only the keywords, but also the title and abstract, with the objective of understanding the most common topics among the collected articles, and the key trends and text characteristics associated with this dataset.

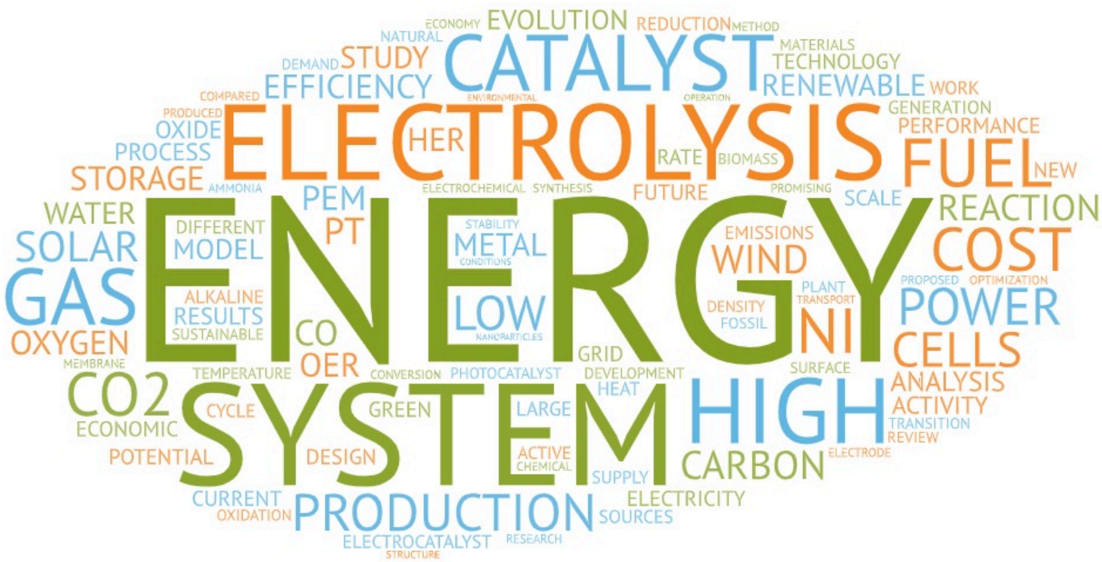

Figure 4.16 – Most frequent words cloud

Figure 4.16 represents the most common 100 words in this dataset. Words such as “Hydrogen” and terms such as “Green Hydrogen”, “Hydrogen Production”, and “Green Hydrogen Production” were removed since these consist of the words used to first extract the current dataset and therefore are extremely common.

The words with highest frequency (Table A 2) are easily explained by the thematic itself. “Energy”, “Electrolysis”, “Catalyst”, “System”, “Production”, “OER”, “HER”, among others, are terms repeated throughout this dissertation, all referring to the green approach to obtain hydrogen and its production methods. Nevertheless, the terms PEM and Alkaline indicate that these two methods are the ones studied the most in this thematic. “Pt” and “Ni” are the most common metals referred, probably when catalysts are discussed. There are also some indicators that the effectiveness of this production method is being studied, such as “Efficiency”, “Performance”, “Potential”, “Optimization” and “Results”. The terms “Supply”, “Cost”, “Transport”, “Storage” and “Economy” indicate that the hydrogen economy is taken into consideration as well, and not only the production phase. In addition, “Renewable Energy”, such as solar and wind, “Sustainable”, and “Environmental” are among the most frequent words, showing that this thematic is associated with clean and sustainable energy. Therefore, the topic analysis throughout the years of the terms “Renewable Energy”, “Sustainability”, “Transport”, “Storage” and “Hydrogen Economy” becomes relevant to study the evolution of these topics.

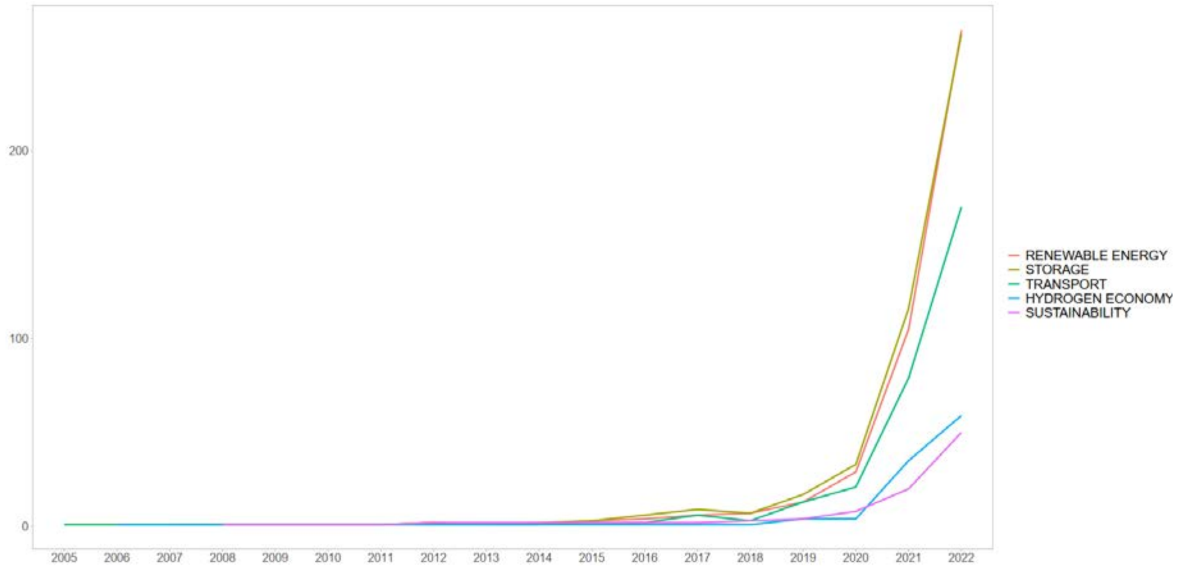

Figure 4.17 – Topic evolution

Until 2015, there was not a significant number of articles referring to these topics. However, after 2015, the terms “Renewable Energy”, “Storage” and “Transport” started to gain popularity and after 2018, the growth tendency accelerated (Figure 4.17). After 2020, the topics grew exponentially, a trend seen often in this dissertation, particularly the “Renewable Energy” and the “Storage” topic. The topics “Hydrogen Economy” and “Sustainability” did not reveal an exponential growth after 2020, not exceeding 50 articles in 2022.

4.3. NETWORK ANALYSIS

The influence and position of countries and institutions in the green hydrogen research also analysed. From the country point of view, China has the highest degree, which means that it has the most connections to the most countries. China has also the highest closeness, which is the country that has the most direct and indirect connections to other countries. When it comes to being the "bridge-country", Germany is leading, that is, it is most central node, due to the number of shortest paths that go through it, becoming an intermediary. Portugal is in fifth place in terms of closeness and in sixth place in terms of betweenness, showing evidence of considerable collaboration with other countries and interest in the thematic (Table 4.4).

Table 4.4 – Country network centrality statistics

Country	Degree	Country	Betweenness	Country	Closeness
China	0.518072	Germany	0.191665	China	0.325490
Germany	0.493976	China	0.180540	UK	0.312030
UK	0.397590	USA	0.149756	Germany	0.307407
USA	0.373494	France	0.136965	USA	0.306273
Italy	0.361446	UK	0.124498	Portugal	0.302920
France	0.361446	Portugal	0.092517	France	0.301818
India	0.349398	India	0.088394	Brazil	0.298561
Spain	0.325301	Russia	0.081445	India	0.297491
South Korea	0.301205	Italy	0.077989	Spain	0.292254
Australia	0.289157	Spain	0.075927	Australia	0.292254

Analysing the country network, there was few VOSViewer configurations. The option of merging the small clusters into larger clusters was selected and the minimum cluster size was set to 16, creating 3 clusters that represent 84 nodes, excluding 4 outlier clusters each composed by one country with no connections to the network (Figure 4.18). The objective behind this minimum cluster size was to create bigger clusters to a more global analysis, rather than having several small clusters.

The network density is 0.13, which means that the proportion of existing links relative to the possible number of links is low. The diameter is four, that is, the length of the shortest path between the most distanced nodes (each connection counts one), and the average path-length is 5.1, which means that there are some steps to give along the shortest path to reach other possible pairs of nodes in the network (Table A 3). In other words, a third node is a bit far from the connection between two nodes, given the size of the network.

There are already some relevant country collaborations, specially between China and other countries, having the highest number of articles shared with Australia, accounting 35 articles – this collaboration represents almost half of the entire Australian production in this matter. The collaboration between China and UK is also very significant for UK since it represents 20% of its total scientific production, and the collaboration between Germany and UK also has some weight (11%). Also, 24% of the scientific productivity in USA comes from collaborative research (Table 4.5).

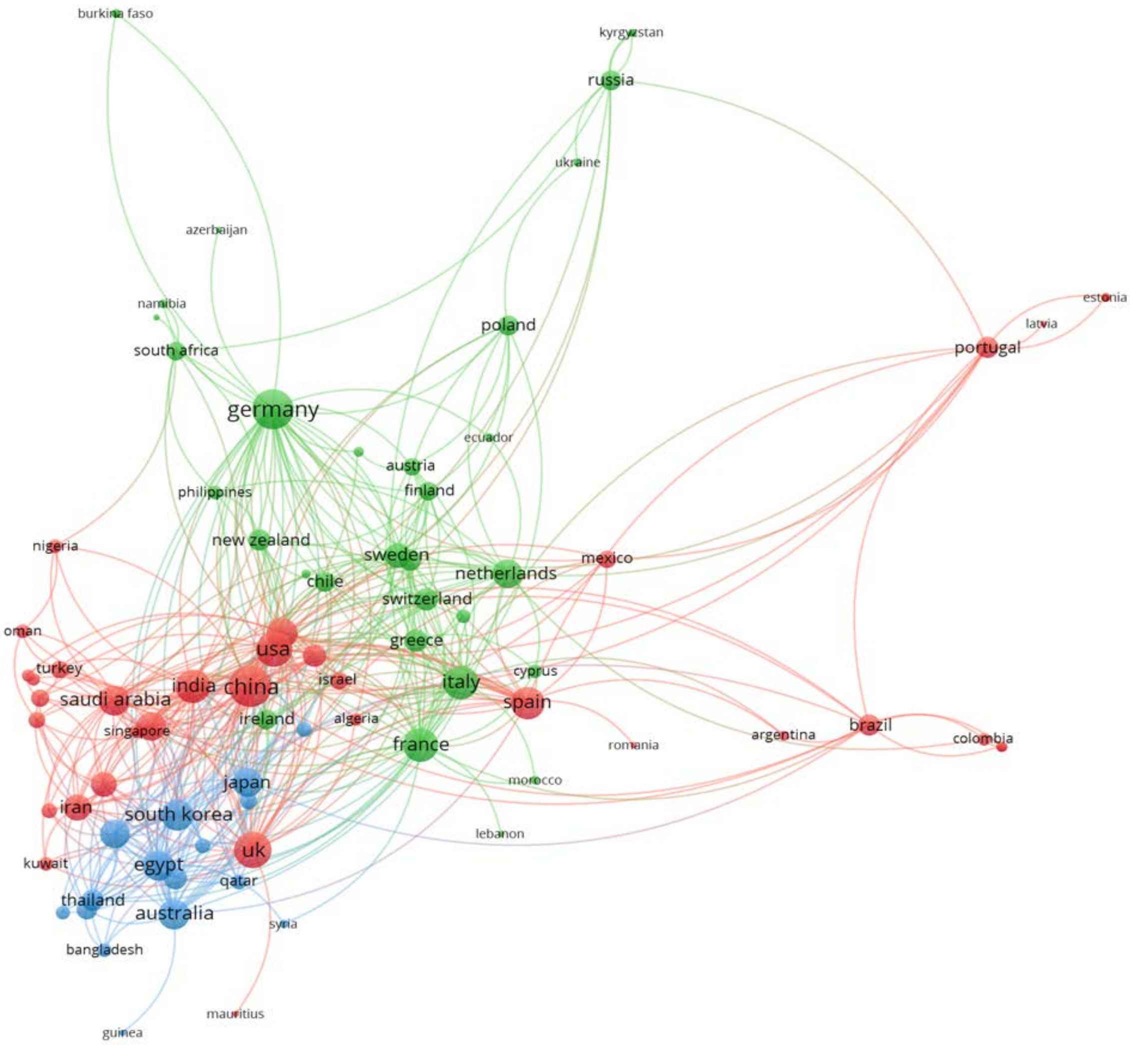

Figure 4.18 – Country Network

Table 4.5 – Top 10 country collaborations

Country	Country	Number of articles
China	Australia	35
China	UK	20
China	USA	20
China	Singapore	15
China	South Korea	13
UK	Germany	11
China	Japan	11
Germany	USA	11
Netherlands	Italy	11
Italy	Spain	11

Portugal does not appear in the top 10 country collaborations. Nevertheless, as seen in Table 4.6, Portugal it has in total 15 articles with other countries, being 5 articles in collaboration with China, representing 33% of the total collaborations and 4 with Spain (27%).

Table 4.6 – Portuguese collaborations

Country	Country	Number of articles
China	Portugal	5
Spain	Portugal	4
USA	Portugal	1
Russia	Portugal	1
Netherlands	Portugal	1
Italy	Portugal	1
Brazil	Portugal	1
Sweden	Portugal	1

Brazil is also an interesting country to analyse. Similar to Portugal, this country is below the technological frontier, and yet it shows dynamism around this new technology, as seen in Section 2.3. In addition, this country is the seven best country in terms of closeness. The Table 4.7 shows the Brazilian collaborations, and even though the number of articles is not big compared to the top 10 collaborations, it is possible to see already some interesting collaborations with countries spread throughout the globe, such as the collaboration with the United States and South Korea.

Table 4.7 – Brazilian collaborations

Country	Country	Number of articles
USA	Brazil	2
South Korea	Brazil	2
Canada	Brazil	2
China	Brazil	1
Japan	Brazil	1
India	Brazil	1
France	Brazil	1

When it comes to the institution analysis, the Tsinghua university, in China, leads in every parameter, degree, betweenness and closeness, which shows that is an important institution to the knowledge production of this thematic (Table 4.8). However, there isn't a single Portuguese institution in the top 10. Also, in the centrality statistics, there is only one institution that is not a university, the German aerospace centre, acting as a "bridge-institution" in 4th place, which can possibly mean that the strongest collaborations happen between universities. On the contrary, when it comes to collaborations between two institutions, Japan leads, and the presence of non-academic institutions is bigger. Taking a closer look to the top 20 strongest collaborations between institutions (Table 4.9), nearly half involve Yokohama National University. The strongest collaboration of 23 articles is between this Japanese University and Nissan Arc, (that stands for Analysis and Research Centre), a Japanese private company. Yokohama National University also has another collaboration of 6 articles represented in the top 20 with the De Nora Permelec Ltd. Although this company is Japanese, it is part of an Italian multinational. The German aerospace centre (a public company) has also a collaboration in 9 articles with the Universitat Stuttgart. This can be a sign of a fruitful connection of academic and non-academic institutions joining forces in this thematic, showing that the knowledge around this thematic is starting to spread outside of universities. However, the strongest collaborations are also from the same country, but it is possible to see already some international connections. Therefore, China, Japan, and Germany show evidence of being strong players in affiliation collaboration.

On a closer note, there is a significant collaboration between two Portuguese institutions: Universidade do Porto and the International Iberian Nanotechnology Laboratory, an investigation centre based in Braga. Although this seems like a national collaboration, the Laboratory has the influence of Spain as well.

Table 4.8 – Affliation network centrality statistics

Affiliation	Degree	Affiliation	Betweeness	Affiliation	Closeness
Tsinghua University	0.108046	Tsinghua University	0.244849	Tsinghua University	0.000213
Massachusetts Institute of Technology	0.087356	Heriot Watt University	0.139481	Université du Québec à Trois-Rivières	0.000202
University of Chinese Academy of Sciences	0.064368	Université du Québec à Trois-Rivières	0.114688	University of Surrey	0.000202
Université du Québec à Trois-Rivières	0.062069	Deutsches Zentrum fur Luft und Raumfahrt DLR	0.111930	Imperial College London	0.000120
Heriot Watt University	0.062069	Massachusetts Institute of Technology	0.103291	Kyungpook National University	0.000120
Imperial College London	0.059770	University of Surrey	0.100997	Tianjin University	0.000195
Norges Teknisk Naturvitenskapelige Universitet	0.057471	Kyungpook National University	0.096772	Cranfield University	0.000194
University of Science and Technology UST	0.057471	King Abdulaziz University	0.079320	Korea University	0.000194
Korea University	0.055172	Nanjing Tech University	0.069510	Yeungnam University	0.000193
Shanghai Jiao Tong University	0.052874	Tianjin University	0.068353	Hong Kong Polytechnic University	0.000193

Table 4.9 – Top 20 affliation collaborations

Institution	Institution	Number of Articles
Yokohama National University	Nissan Arc, Ltd	23
Rheinisch Westfalische Technische Hochschule Aachen	Forschungszentrum Julich FZJ	9
Yokohama National University	Waseda University	9
Universitat Stuttgart	Deutsches Zentrum fur Luft und Raumfahrt DLR	8
Yokohama National University	Hirosaki University	7
Yokohama National University	Universite de Poitiers	7
Norges Teknisk Naturvitenskapelige Universitet	Universite du Quebec a Trois Rivieres	7
Waseda University	Waseda Institute for Advanced Study	7
Yildiz Technical University	Ontario Tech University	6
Yokohama National University	De Nora Permelec Ltd	6
Yokohama National University	Waseda Institute for Advanced Study	6
University of Chinese Academy of Sciences	Shanghai Advanced Research Institute, Chinese Academy of Sciences	5
Universidade do Porto	International Iberian Nanotechnology Laboratory	5
Homi Bhabha National Institute	Bhabha Atomic Research Centre	4
Sejong University	Dongguk University, Seoul	4
Tsinghua University	Institute of Metal Research	4
Academy of Scientific and Innovative Research AcSIR	Central Electrochemical Research Institute India	4
Sun Yat Sen University	School of Mechanical and Aerospace Engineering	4
Ulsan National Institute of Science and Technology	Yale University	4
Dhofar University	Ecole National d'Ingenieurs de Monastir	4

The affiliation network also had few VOSViewer configuration to achieve this layout. The option of merging the small clusters into larger clusters was selected and the minimum cluster size was set to 80, creating 3 large clusters, to have a more global analysis, rather than having more than 30 small clusters. This network represents 436 affiliations and excludes 13 noisy clusters that don’t communicate with the network shown in (Figure 4.19), which can be already an indicator of a lack of collaboration. The main statistics (Table A 4) show how far is a third node from the connection of other two nodes since the average length path is almost 19. The density of the graph is 0.01, showing that this network is sparse, and its diameter is 8. All these indicators, given the size of the network, show there is few links (connections) between nodes (institutions), which means that the collaboration level between institutions is low.

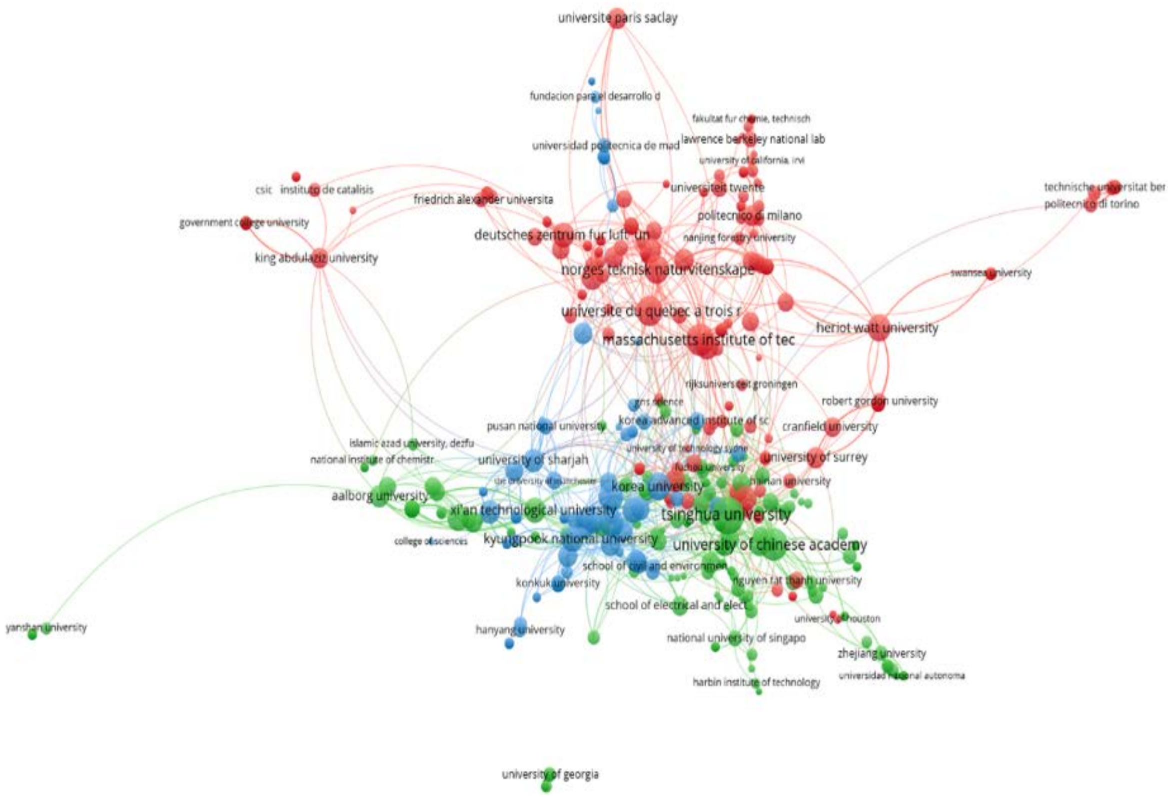

Figure 4.19 – Affiliation network

5. CONCLUSION

In this dissertation, we conducted a comprehensive scientometric analysis of the Green Hydrogen thematic, aiming to understand its evolution, key contributors, and emerging trends. The dissertation covered a wide range of aspects, from the growth of scientific publications to network analyses of countries and institutions.

Green Hydrogen research showed remarkable growth, especially in recent years. The burst of scientific production started after 2020 and highlights the increasing global interest in Green Hydrogen as a sustainable energy solution.

China is identified as a dominant force in Green Hydrogen research, leading in both the number of articles published and citations. Other countries, such as Germany, South Korea, the USA, and Japan, also made significant contributions. All these five countries show an exponential growth trend after 2020. Regardless, European countries, driven by initiatives like the European Green Deal and their own national roadmaps, demonstrated their commitment to Green Hydrogen, when looking to the affiliation of first authors. Portugal is the country with the highest number of first-author articles per million inhabitants, having 2.53 authors/million.

In new knowledge creation, the leading actors are mainly research institutions. Japanese institutions lead the number of articles, but when it comes to citations, it is Cyprus University of Technology that leads. Universidade do Porto has 18 articles published and several citations, confirming the effort Portugal is making on the thematic.

Based on the keywords and most frequent words analysis, several evolving trends were revealed, especially when it comes to production methods and its efficiency. By being directly associated to the research topic, keywords like “Hydrogen Production”, “Water Electrolysis”, “Oxygen Evolution Reaction” and “Hydrogen Evolution Reaction” are the most used. In specific, “PEM Water Electrolysis” and “Alkaline Water Electrolysis” gained prominence throughout the years, for being the most suitable technology to produce green hydrogen so far, especially PEM since it handles the intermittent power. Also, the possibility of using recycled materials in the catalysts points to the circularity perspective that can be associated to this thematic as well. Nevertheless, the growth of the terms “Life Cycle Assessment” and “Renewable Energy” can show that the focus on this thematic is not only on its production method, but also in the green hydrogen economy. A direct relationship between the keywords and most frequent words is made since most of words refer to production method techniques and its specifics. Additionally, terms as “Renewable Energy”, “Sustainability”, and other steps of the chain of value rather than just production (“Storage” and “Transport”) are evidenced, pointing to the rising interest of the green hydrogen economy.

Network analysis showcased the global collaboration patterns in Green Hydrogen research. By the conclusions taken from the networks and the Herfindahl Index, it is possible to observe that throughout the years, the knowledge production is being more evenly distributed across countries, showing a more diverse pattern, and not a monopoly of knowledge, as collaborative research represents a significant share of the scientific production for several countries.

Once again, China appears to be a stronger actor in the country network, by having the highest degree and closeness. Nevertheless, Germany plays a vital role in the network, acting as bridge country, facilitating connections between other countries.

In the affiliation network, although the network reveals to be sparse, it is possible to see already some interesting patterns. The Tsinghua University is dominant, acting as the bridge institution as well as the being the one with the highest degree and closeness, showing how active this institution is in the thematic. However, when taking a closer look to the strongest collaborations between two institutions, the landscape is different. Japan has the strongest collaborations, followed by Germany. Most connections are on a national level, but some international ones are starting to appear too. Non-academic institutions like Nissan Arc, the German aerospace centre, Forschungszentrum Julich FZJ, and De Nora Permelec Ltd are demonstrating a more spread interest in the Green Hydrogen field, showing that the knowledge is not fully concentrated in the university community. Nevertheless, some of these institutions are research centres and have strong connections to academic institutions.

Portugal is an active participant in both networks, with strong values of closeness and betweenness. Also, it has relevant collaborations with China and Spain. When it comes to its institutions, there is a strong connection between Universidade do Porto and International Iberian Nanotechnology Laboratory, which highlights the joint effort these institutions are making to contribute to the international Green Hydrogen research.

Brazil also stands out in terms of research in this new technology, already showing some interesting collaborations with major players: United States, South Korea, China and Japan.

Although this dissertation provides valuable insight into the current state and knowledge distribution of the Green Hydrogen thematic, there is still work to be done. In addition, the scientometric approaches to this new technology development remain scarce.

The technologies to produce Green Hydrogen need deeper research in terms of efficiency and scalability, specifically in the PEM Water Electrolysis and Alkaline Water Electrolysis, since they are proven to be the leading technologies to use. The environmental impact also needs special attention, since this production method should contribute to the NZE, and that involves being sustainable in the entire chain of value. As seen, the use of materials as Pt has an environmental impact. Also, although the interest is rising, there is still information missing around other steps of the hydrogen value chain, such as storage, transportation, and policy and market frameworks. A holistic stance on the enhancement of hydrogen economy will play a strong role in the green hydrogen research, since alternatives to conventional power sources must consider the sustainability of technological patterns.

The collaboration between institutions is promising but it is necessary to encourage those joint forces to accelerate improvements in the research and to help countries to successfully achieve their roadmaps milestones, especially if that allows interdisciplinary connections such as engineering, economics, and environmental sciences.

To conclude, Green Hydrogen shows evidence of being a technology that can contribute a sustainable economy and also to being in the right path to achieve the net-zero emissions, since it contributes for clean and sustainable energy production. This dissertation provides valuable insights into its research landscape.

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APPENDIX

Table A 1 – Re-classification of scopus categories into generic ones

Scopus Categories	Aggregated category Groups
energy & fuels	Energy
materials science	Exact Sciences
science & technology – other topics	Science & technology
chemistry	Exact Sciences
electrochemistry	Exact Sciences
computer science	Engineering
engineering	Engineering
metallurgy & metallurgical engineering	Engineering
education & educational research	Social Sciences and Humanities
polymer science	Exact Sciences
physics	Exact Sciences
environmental sciences & ecology	Environmental sciences
thermodynamics	Exact Sciences
mechanics	Exact Sciences
biotechnology & applied microbiology	Life Sciences
food science & technology	Life Sciences
nuclear science & technology	Exact Sciences
business & economics	Social Sciences and Humanities
telecommunications	Engineering
mineralogy	Natural Sciences
mining & mineral processing	Engineering
crystallography	Exact Sciences
transportation	Engineering
geology	Natural Sciences
meteorology & atmospheric sciences	Natural Sciences
oceanography	Natural Sciences
water resources	Natural Sciences
construction & building technology	Engineering
agriculture	Natural Sciences
biochemistry & molecular biology	Life sciences
biophysics	Life sciences
spectroscopy	Life Sciences
fisheries	Engineering
marine & freshwater biology	Natural Sciences
international relations	Social Sciences and Humanities
microbiology	Life Sciences
public, environmental & occupational health	Social Sciences and Humanities
acoustics	Exact Sciences
automation & control systems	Engineering
mathematics	Exact Sciences

communication	Social Sciences and Humanities
operations research & management science	Social Sciences and Humanities
instruments & instrumentation	Life Sciences
robotics	Engineering
government & law	Social Sciences and Humanities
area studies	Social Sciences and Humanities
geography	Social Sciences and Humanities

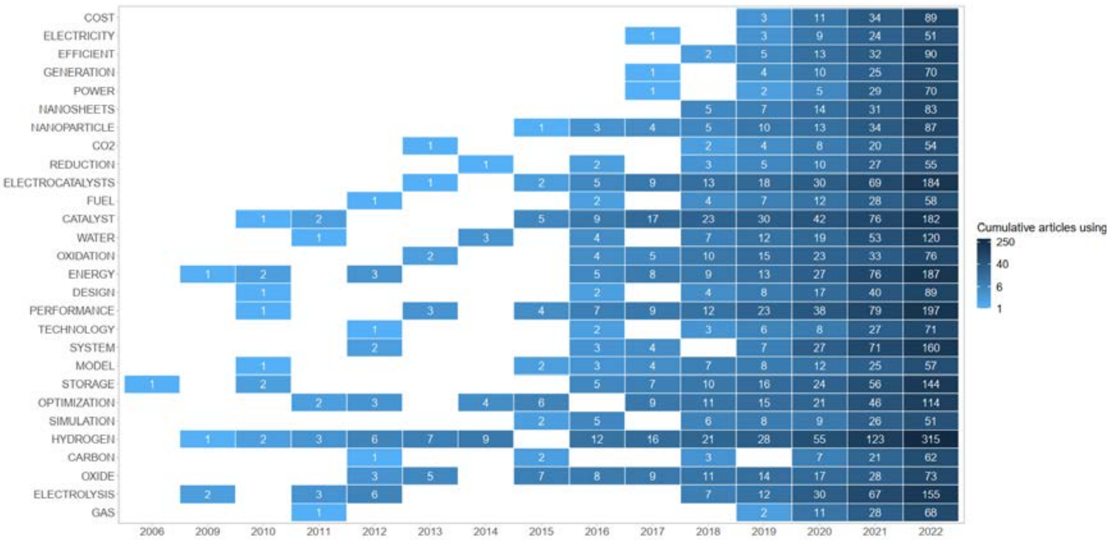

Figure B 1 – Keywords Unigram

Table A 2 – Frequency of the 100 most frequent words

Words	Frequency
Energy	4277
Electrolysis	2504
System	1915
Catalyst	1830
Production	1776
High	1504
Fuel	1467
Cost	1462
Power	1375
Efficiency	1349
Renewable	1349
Gas	1235
Carbon	1207
Reaction	1084

Evolution	1053
Electrocatalyst	1006
Cells	999
CO2	958
Storage	958
Performance	954
Technology	951
Oxygen	870
Solar	842
Electricity	799
Analysis	772
Wind	725
Study	724
Low	710
Process	682
Water	679
Metal	673
Potential	672
Current	661
Generation	634
Reduction	603
Economic	600
Activity	570
Results	570
Model	568
Development	532
Oxide	531
Emissions	526
Different	512
Future	485
Design	475
OER	468
Green	454
Photocatalyst	438
Alkaline	433
Sources	424
PEM	423
Temperature	419
Electrochemical	398
Sustainable	397
Materials	395
NI	394
Transition	392
Oxidation	390
Surface	388

Natural	386
Optimization	384
HER	380
Scale	379
Density	378
Membrane	378
Supply	372
Stability	367
Conversion	366
Active	361
Promising	353
CO	351
Large	350
Proposed	338
Work	338
Synthesis	329
Research	327
PT	326
Electrode	325
Biomass	323
Transport	322
Economy	321
Demand	320
Ammonia	319
Cycle	318
Environmental	318
New	318
Fossil	317
Review	317
Operation	311
Plant	308
Conditions	306
Chemical	304
Grid	301
Compared	299
Produced	299
Method	296
Heat	292
Nanoparticles	291
Rate	291
Structure	290

Table A 3 – General statistics of the country network analysis

Metric	Value
Size	84
Density	0.12736661
Transitivity	0.40855475
Diameter	4
Average Path Length	5.09150889
Centrality Degree	0.39070568
Centrality Betweenness	0.14659681

Table A 4 – General Statistics of the institution network analysis

Metric	Value
Size	436
Density	0.01758937
Transitivity	0.4912844
Diameter	8
Average path length	18.1433724
Centrality Degree	0.09045661
Centrality Betweenness	0.14903704
Centrality Closenness	0.23800436