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A STATISTICAL ANALYSIS OF SCIENTIFIC RESEARCH AND THE ENERGY PROJECTION OF GREEN HYDROGEN AT A GLOBAL LEVEL IN THE LAST FIVE YEARS

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ABSTRACT
Seeking energy sources with low volume of carbon emissions has boosted the energy market and global scientific research. From this point, the objective of this study is to verify with the help of a bibliometric analysis the progress of research on energy renewal based on the production of green hydrogen, the installed capacity, the academic institutions that are at the forefront of this movement, authors and journals that have emphasized the subject. The methodology used was based on bibliometric research elaborated with the support of the bibliometrix data package through the RStudio software, carried out in the Scopus and Web of Science databases. Search expressions ("green hydrogen") and ("low carbon emission") or "decarbonization" or "greenhouse gases", were used in order to reach the widest possible range of action, these expressions were initially filtered based on the time period between 2019-2024, followed by the filter of review articles, conference papers, open access, written in English. A total of 913 studies were surveyed, with 8 duplicate articles, and in the end, 885 unique articles remained that fit the theme, the search expressions, and the filters placed. Initially, there was an annual search growth of 128%, where the biggest subjects searched were the production of hydrogen, fossil fuels, low carbon, electrolysis, hydrogen storage, green hydrogen.

Keywords: Academic Research. Energy Market. Authors. Articles. Journals.

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INTRODUCTION

The global alert of climate change arising from greenhouse gas emissions has resulted in a series of consequences that have provoked scientific research in the search for solutions. Aiming to seek socioeconomic development with the interaction in environmentally stable solutions and lower consumption of natural resources. (SHAO, 2024)

The search for fuels with a lower volume of atmospheric emissions, such as the use of oleofins derived from catalytic pyrolysis of plastic waste as fuel, low-carbon renewable sources such as lignin, ethanol, in addition to the use of photovoltaic energy on an increasing scale, are some of the actions that have been sought with the purpose of optimizing production, while prioritizing sustainability. (GOSHAYESHI et al., 2024) (KUMAR et al., 2024) (DONG et al., 2024) (GHASABAN et al, 2025) (SALMANI MARASHT et al, 2024)

HERRANDO et al.,(2023) in their study, they discuss the importance of implementing renewable energies in order to mitigate carbon emissions, which is salutary, as it refers to the latent and urgent need to mitigate anthropogenic impacts and reduce CO2 emissions. When talking about anthropogenic impacts, it is necessary to think about all points of the process, the dependence on non-renewable energy matrix, the high consumption of energy for production, the existence of recycling programs and the low adherence to them by the population, all these bottlenecks are agglutinating in such a way as to also become a public health problem. These are challenges that need to be faced more pragmatically by the agents of the entire process, industries, commerce, political managers, consumers. (ABED et al., 2024) (YANG et al., 2023)

Based on the data presented, it is observed that the proposal for the implementation of the circular economy, low effectiveness solid waste recycling projects, although relevant, do not provide satisfactory results for the purpose of mitigating CO2 emissions by the planet. Decarbonizing, as they propose, is no longer a utopian opportunity, but a necessity. Thus, as a viable alternative, the production of "green hydrogen" as an alternative source of the energy matrix emerges, being techniques that combined can present relevant immediate and sustainable results, due to its versatility and adaptability, which are the essential components of an energy future. (GODE et al, 2024) (TAOUOURIA, 2024) (GUO et al, 2023) (HERNANDEZ et al., 2024) (KHOSRAVITABAR et al,2024)

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The prospect of green hydrogen as a substitute fuel for the fossil matrix and demonstrates the capacity of this product as a clean and renewable source, has become increasingly promising and real. It is true that the proposal of green hydrogen as a fuel is auspicious, it requires several efforts in research and development, collaboration between researchers for transfer and technological investment to increase the feasibility of hydrogen production. (AHMAD et al., 2024) (HASSAN et al, 2024) (ABDIN et al., 2020)

A productive bottleneck for hydrogen lies in the high energy consumption of its electrolyzers, which are the pickups and feeders of the hydrogen electrolysis process, its need for electric current stability for optimized production. To this end, energy use control strategies have been researched and explored to resolve these critical points, the degradation of the electrolyzer is also a factor that also draws attention to its use at high temperatures and in the absence of current stability, stops and restarts are constant, leading to loss of productive capacity. (WANG et al., 2024) (RAHMAN et al, 2024) (KUANG et al., 2024)

The technological cost of implementing a hydrogen production system is high. In order to reduce and mitigate this bottleneck, they present a study where the energy fluctuation is solved with the coupling of a photovoltaic module to the system, also, more and more sustainable technologies for cleaner production are increasingly formalized, where a dynamic system of alkaline electrolysis raises operational conditions of production. It is then observed that the technology demands constant energy, optimization modeling of multi-electrolyzers (WANG et al., 2024), in addition to more accurate mathematical modeling. (ZHOU et al, 2024) (QI et al., 2023) (INGENUITY, 2024)

It is then observed that the proposal for large-scale use of green hydrogen is healthy, it has faced challenges that research seeks through interactions between researchers and resolutions, and that energy consumption for production is high and needs strategic alternatives. Thus, this analytical study aims to raise current information on the progress of research on this topic presented above, the growth of searches in the literature that will be converted into new studies, the researchers committed to this purpose, their research partnerships, as well as the institutions that originate new research and the fruits of work in the form of innovations and articles published in consolidated journals throughout the planet.

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APPLIED METHODOLOGY

To carry out this specific study, a search was carried out in the Scopus and Web of Science databases with the following search expressions: ("green hydrogen") and ("low carbon emission") or "decarbonization" or "greenhouse gases", as these expressions address in a synthesized way what is intended in this bibliometric analysis. The search time span was defined for the last five years (2019-2024), papers in English were accepted, only articles were accepted, and book chapters, books, conference proceedings were excluded.

In all, 913 works were found, distributed in 479 raw files in Scopus and 414 in the Web of Science, which after the removal of 8 duplicate files resulted in 885 studies that make up this bibliometric analysis work. The files were obtained in a research carried out on the Capes periodicals database, exported to the Rstudio software, treated, filtered, and finally grouped by the Biblioshiny function of the Bibliometrix data package of the referred software, from which a report was obtained that composes the bibliometric analysis that follows in this study.

The construction of the reasoning in the support texts was based on search expressions such as: ("keywords") and ("scientific relevance"), ("authors") and ("relevance of publications"), ("scientific research") and ("logical foundation"), ("cluster formation") and ("scientific relevance"), ("trend map") and ("scientific research"), surveyed in the Wiley, Springer Nature, Scopus, Web of Science databases, based on the temporal span of years (2016-2024), This three-year variation is explained by the fact that the subject of green hydrogen as an energy source is no longer a technology totally unknown to the scientific community.

RESULTS

The main information contained in the object that generates the file with the 885 articles is shown in Figure 1 below, and is related to research sources, affiliations, author's keywords, in addition to the number of studies surveyed, the annual growth of searches, average citations and the average time of each article.

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Figure 1 - Main information obtained in relation to documents, annual growth, time spacing, sources, authors, author keywords, international co-authorship, average number of co-authors per document, age of documents

Source: Biblioshiny Report

With only 8 duplicate articles out of a total of 913 articles searched, this study presents a relevant interest of the scientific community regarding the theme suggested in the previously mentioned search expressions. The annual growth rate was 128% per year and part of the interest in the search for renewable sources and alternatives to the existing fossil fuel energy matrix. The documents have a good percentage of citations of 16.38 per document, as well as international co-authorship of 15.25% indicating the relationships of researchers, in addition to a low average age per document of 1.64 years, reinforcing the topicality of the theme in the research scenario.

Table 1 below shows the annual production of articles related to the topic, there is a low volume of productions in 2019, justifiable because it is a period related to Covid-19, the jump to later years is well defined in the annual growth previously presented, although a trend line is created as there is an increase in publications observed by the number of citations, There is a decrease in the average number of citations per year.

Table 1 - Related citations by author/year of the studies researched, encompassing the average per article and the average annual citations.

Anus	Average citations per article	Number of citations	Average Citations per annum	Annual citations
2019	509	3	84,83	6
2020	31,95	87	6,39	5
2021	32,63	129	8,16	4
2022	17,64	220	5,88	3
2023	6,8	258	3,4	2
2024	1,82	188	1,82	1

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Source: Biblioshiny Report

1 SOURCES RESEARCHED

A total of 459 research sources were obtained, as previously discussed, only scientific articles related to this bibliometric analysis. Table 2 below presents the first 10 sources obtained in this study, which is only a reduced presentation of the total number of sources, as well as a leaner view of the importance of the journal in the construction of a scientific trend.

Table 2 - Excerpt from the biblioshiny report, presenting only 10 sources and the number of articles published in these sources

Sources	Articles
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	57
ENERGIES	37
JOURNAL OF CLEANER PRODUCTION	31
APPLIED ENERGY	19
ENERGY	17
FUEL	16
ENERGY CONVERSION AND MANAGEMENT	15
MATERIALS TODAY-PROCEEDINGS	11
ENERGY POLICY	10
CHEMICAL ENGINEERING JOURNAL	9

Source: Biblioshiny Report

RELEVANT AUTHORS, PRODUCTION OVER TIME, MOST CITED WORKS GLOBALLY

The main information contained and presented in Figure 1 of this analysis points to a co-authorship of 4.78 researchers per published work (GU et al., 2017). This growth relationship pointed out above is based on crucial points and aspects relevant to good scientific research. The conceptual approach is facilitated by a vast availability of current data and information within scientific research provided by journals with very careful and reliable indexing indexes and, providing prominence to authors, favoring a greater number of publications and relevance of documents as pointed out in an excerpt from the original document of the report in Table 3 below, where only 22 sources are highlighted divided among three authors. (KONG et al., 2019) (HACKMAN et al, 2024)

Table 3 - Excerpt from the biblioshiny report, including authors, annual productions, sources, DOI and total citations by documents

Author	Anus	TWO	Total Citations	Citations by year

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WANG Y	2024	10.1016/j.watres.2024.121576	9	9
WANG Y	2024	10.1016/j.gee.2023.02.011	9	9
WANG Y	2024	10.1016/j.applthermaleng.2024.123067	3	3
WANG Y	2024	10.1016/J.Jechem.2023.11.026	8	8
WANG Y	2024	10.1016/B978-0-443-28824-1.50158-7	0	0
WANG Y	2023	10.1016/j.seppur.2023.123957	10	5
WANG Y	2023	10.11896/cldb.22040218	0	0
WANG Y	2023	10.1007/s40843-023-2608-6	3	1,5
WANG Y	2023	10.1360/TB-2023-0531	2	1
WANG Y	2022	10.1016/j.energy.2022.123181	10	3,33333333
WANG Y	2022	10.1080/27658511.2022.2062824	17	5,66666667
WANG Y	2021	10.1016/j.mtphys.2021.100551	5	1,25
WANG Y	2021	10.1016/j.jcis.2021.02.005	34	8,5
WANG Y	2021	10.11698/PED.2021.02.18	125	31,25
WANG Y	2021	10.1016/j.ngib.2021.08.009	84	21
WANG Y	2021	10.13228/j.boyuan.issn0449-749x.20210170	6	1,5
WANG Y	2021	10.3787/j.issn.1000-0976.2021.08.005	50	12,5
WANG Y	2021	10.1016/S1876-3804(21)60039-3	324	81
ZHAO Y	2024	10.13335/j.1000-3673.pst.2023.1233	2	2
WANG J	2024	10.20138/j.cnki.issn1002-106X.2024.04.002	0	0

ANALYSIS OF THE AUTHOR'S KEYWORDS, CO-OCCURRENCE NETWORK, THEMATIC MAP

There are 3040 keywords of the author, used by 3050 authors, which indicates the collaboration and variety of researchers working on the theme, distributed in 459 different sources in 885 articles obtained in this bibliometric analysis. The summarization of research data carried out through bibliometric analysis emerges as a support tool in several areas of knowledge (GUIMARÃES et al,, 2019; HINTZEN et al., 2020; RIBEIRO, 2020).

When performing a search on a certain subject, the relevance of the appropriate keyword is verified to make it a search expression. Thus, in this study, of the ten most relevant words presented in Figures 2 and 3, six of them correspond to 19.8% of the total uses, they are: hydrogen production (0.07%), CO2 (0.04%), hydrogen storage (0.03%), carbon (0.03%), green hydrogen (0.03%) and hydrogen (0.03%).

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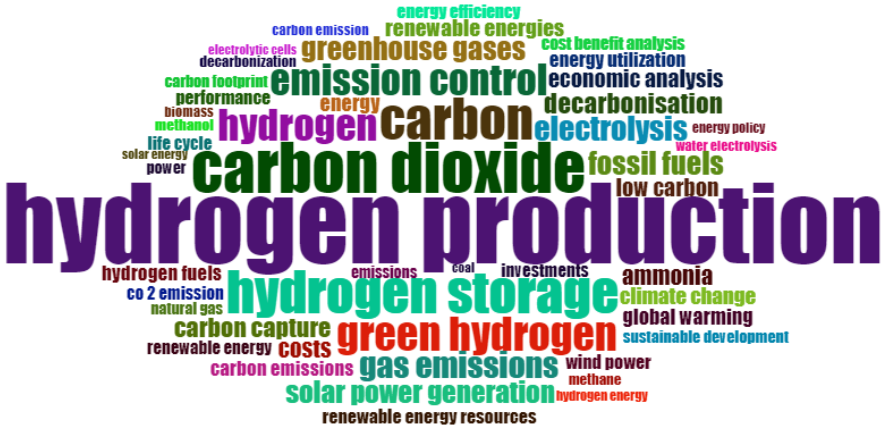
Figure 2 - Cloud of verified words and sampling of 50 of the author's most used keywords in this bibliometric analysis, highlighting the production of hydrogen, carbon dioxide, hydrogen, energy, emission control, fossil fuels, low carbon.



Source: Information according to a report generated by biblioshiny

Therefore, from the words most used by authors, the bibliometric analysis generates a network of co-occurrence Figure 3, where "clusters" of expressions are formed. The partitioning of research data into clusters is a safe way to offer completeness and transparency to research, allowing the mining of the flow of data obtained, facilitating its management, as well as offering future research an organized source of data. This random grouping generates the clusters nodes by deriving results from component groupings transferred to master nodes. These master nodes can be easily observed in Figure 4 below, and represent a trend obtained from total data of the surveys carried out and that aimed at the expected products in the form of articles. (MAHMUD et al., 2023)

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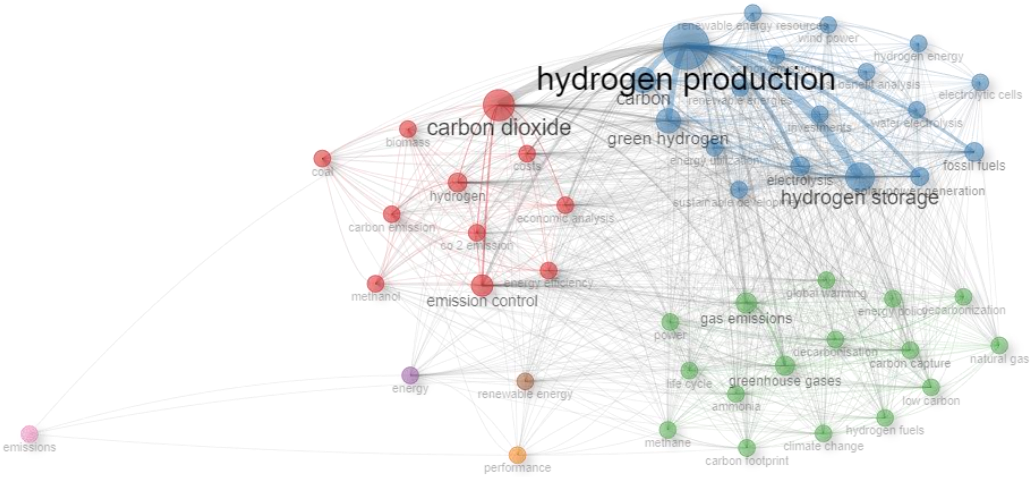
Figure 3 - Co-occurrence network formed from the most relevant words: hydrogen production, hydrogen storage, green hydrogen, carbon dioxide, emission control, gas emissions, fossil fuels



Source: Information according to a report generated by biblioshiny

The thematic map presented in Figure 4 below is established as a graphic and growing representation of the most discussed themes. There is a clear ascent from the second quadrant, passing through the third, fourth and having its apex in the first quadrant of the plane. Topics such as energy recovery and generation, greenhouse gases, CO2 management, life cycle systems, formed few clusters of relationship. On the contrary, and showing growing interest by the researchers, are the performance of systems, combustion and temperature in China, energy renewal, biomass in methane production, with energy coming from hydrogen, carbon electrolysis, and hydrogen production among the relationships of greatest search, production, and publication of articles evidenced in this study.

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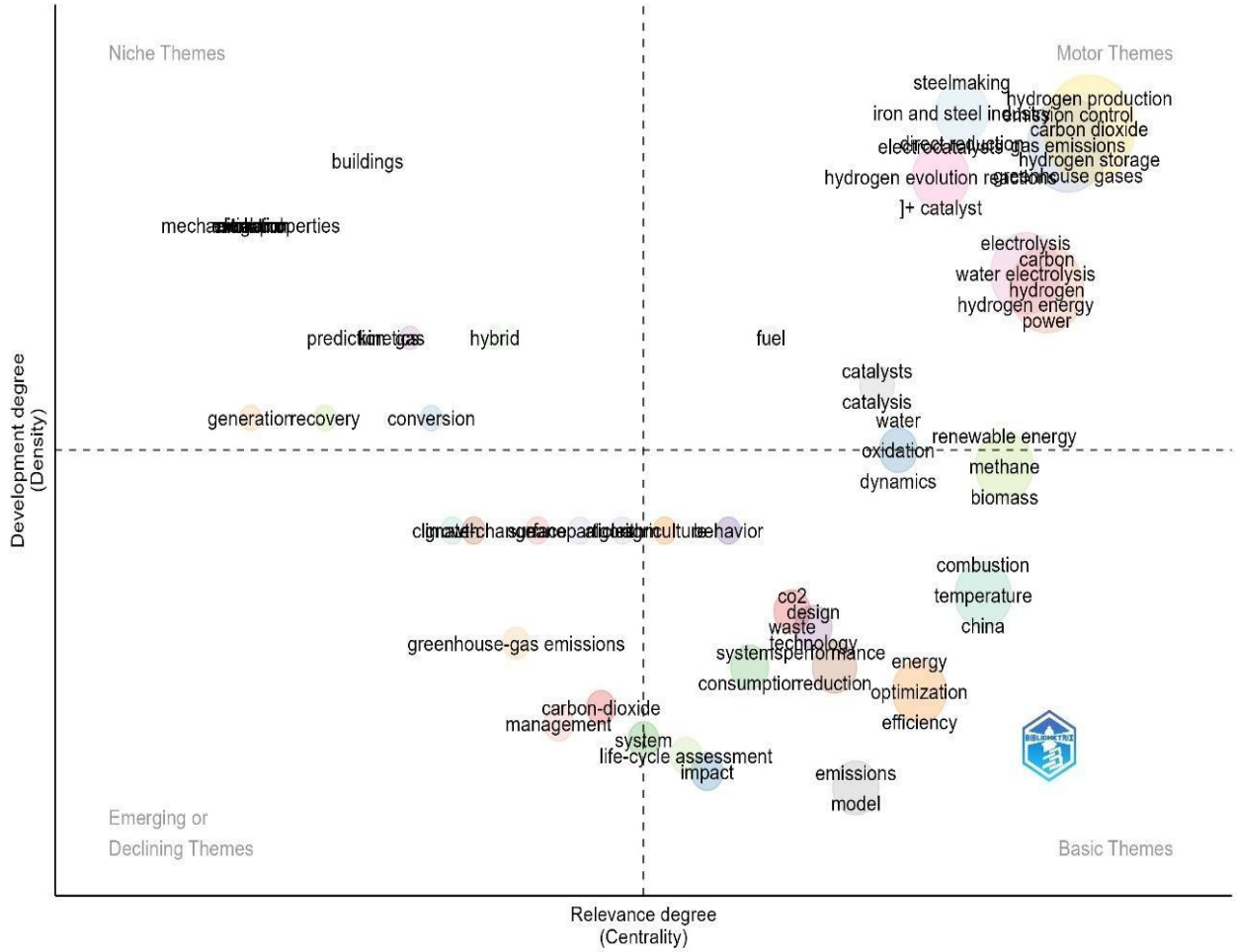
Figure 4 - Thematic map of trends in research and publications, several clusters were formed, hydrogen production, continuous emissions, electrolysis, carbon, hydrogen, combustion, energy and steel production being the most relevant clusters, all with citations above 35 times



Source: Information according to a report generated by biblioshiny

COLLABORATION NETWORK

There is a well-formalized and established academic trend in the thematic change of a journal (BAKER et al., 2021), this path is observed mainly by the size of mined data files that help the construction of this reasoning. Thus, the demand for collaborative expansion between researchers and countries arises, as can be seen in Figures 5 and 6 below. (VANHALA et al., 2020)

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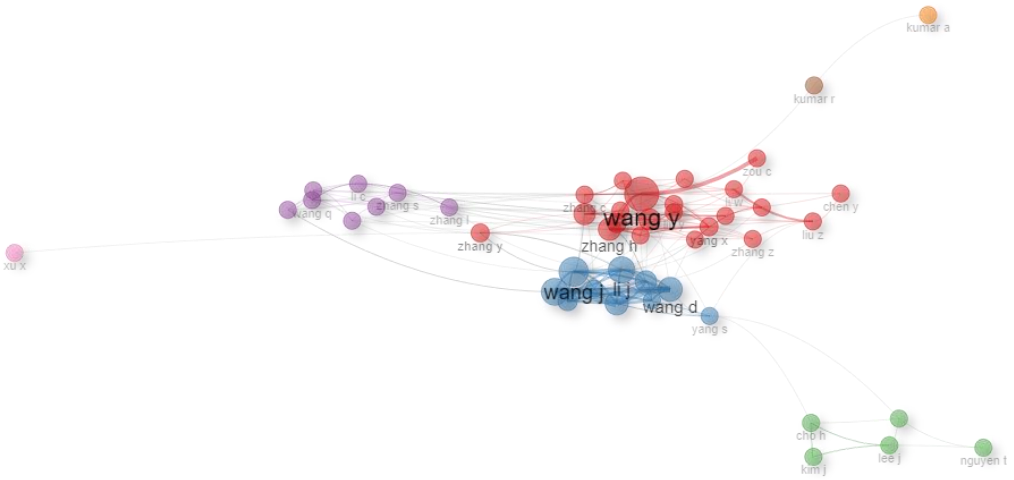
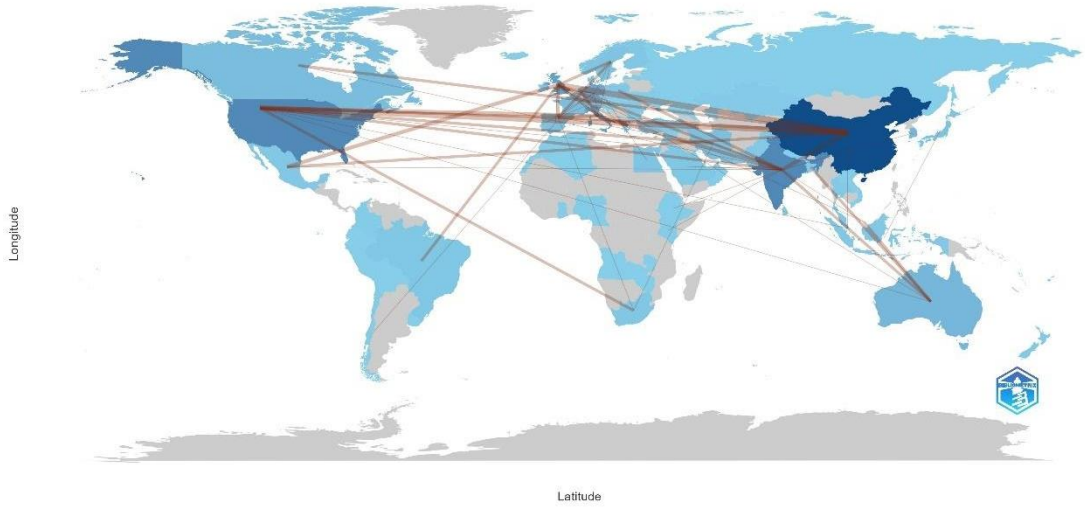
Figure 5 - Collaboration Network between authors, highlights between Wang W, Zhang H, Yang X, Zhang Z, with Zhang Y, Zhang I and Zhang S on the left, below with Wang J, Li J, Wang D.



Source: Information according to a report generated by biblioshiny

Figure 6- Map of global collaboration related to this study, dark blue color indicates higher rates of collaboration, as the color is less intense, the lower the collaboration between countries



Source: Information according to a report generated by biblioshiny

The survey that generated this analysis, based on data extraction, purification and literature review, shows that 317 publications were shared, involving 70 countries mentioned that sought data with 37 nations through cooperation to expand a global collaboration network on the themes and trends researched. China stood out with the highest number of publications, with 49 articles shared by 24 authors. However, France presented 16 publications shared with 6 countries, obtaining the highest number of shares and Sweden was the one that interacted the most, keeping in touch with 8 countries and 13 publications. However, researchers from the United Kingdom lead in relation to those who contributed the most, with 47 articles and the largest sharing of information went to Mexico

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and France with 4 productions, followed by Brazil, Greece and Sweden with 3 publications, as shown in Table 4 below.

Table 4 – Presentation via clipping table obtained in a report of the Bibliometrix package through biblioshiny, where the network of collaboration between countries with the respective shared studies and their frequency is demonstrated .

From	To	Frequency
AUSTRALIA	BANGLADESH	3
AUSTRALIA	DENMARK	1
AUSTRALIA	INDONESIA	1
AUSTRALIA	IRELAND	1
AUSTRALIA	LAOS	1
AUSTRALIA	MALAYSIA	3
AUSTRALIA	NORWAY	1
AUSTRALIA	PAKISTAN	1
AUSTRALIA	SAMOA	1
AUSTRALIA	SINGAPORE	1
AUSTRALIA	TURKEY	1
AUSTRALIA	U ARAB EMIRATES	1
AUSTRALIA	VANUATU	1
BELGIUM	CAMEROON	1
BRAZIL	AUSTRIA	1
CANADA	BANGLADESH	1
CANADA	IRAN	1
CANADA	NETHERLANDS	1
CANADA	U ARAB EMIRATES	1
CHINA	ANGOLA	1
CHINA	AUSTRALIA	1
CHINA	BANGLADESH	1
CHINA	BELGIUM	1
CHINA	CANADA	3
CHINA	DENMARK	1
CHINA	ETHIOPIA	1
CHINA	FRANCE	3
CHINA	GERMANY	1
CHINA	GHANA	1

Source: Information according to a report generated by biblioshiny

GLOBAL ENERGY TRANSITION AND PROSPECTS

GLOBAL ENERGY TRANSITION

To date, the disposition of the literature points to the need for the energy transition of the current matrix to renewable sources that do not emit as many greenhouse gases as fossil fuels (SHANG et al., 2024). The increase in the Earth's temperature due to

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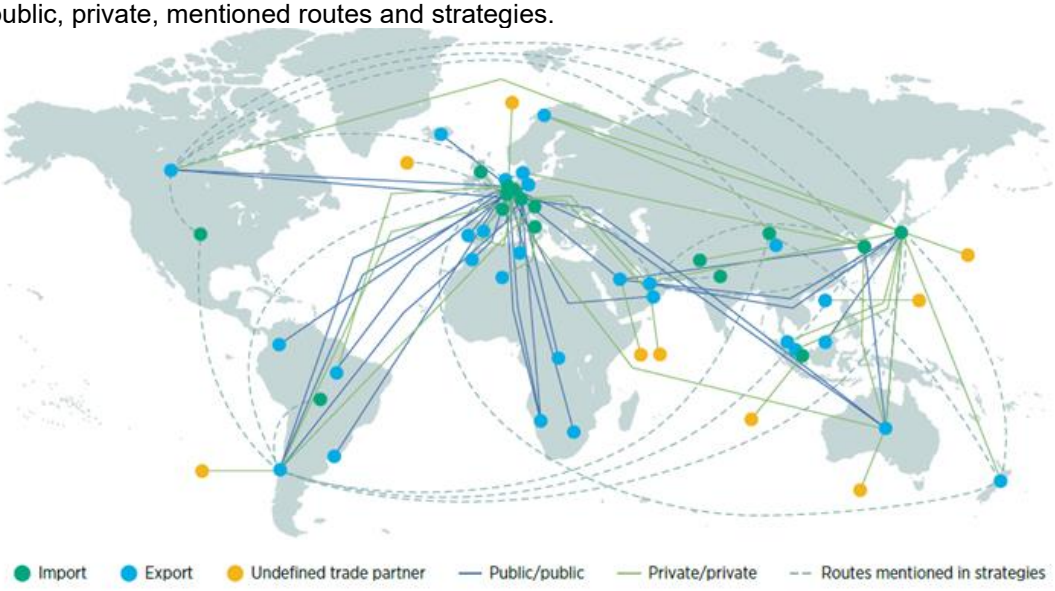
anthropogenic emissions is a significant factor for the acceleration of the energy transition (USMAN et al, 2022).

Therefore, as presented so far by this bibliometric analysis, the role of discussion, technology transfer, and research collaboration are crucial at this time that the planet is experiencing to find technical and financial feasibility in the implementation of renewable energy sources (ADEDOYIN et al., 2021; HANIF et al, 2019; QAMRUZZAMAN et al, 2020).

The success of the energy transition depends on a transformation of the global energy sector from fossil sources to zero-carbon sources by the second half of this century, reducing energy-related CO2 emissions to mitigate climate change and limit the global temperature to 1.5° of pre-industrial levels (IRENA, 2023).

Figure 7 – Global geopolitics for hydrogen production and distribution, highlighting import, export, trade partner, public, private, mentioned routes and strategies.



Source: Information according to a report generated by biblioshiny

PROSPECTS IN HYDROGEN PRODUCTION

In its newsletter, IRENA (2023) points out the cost of the electrifier as still being a bottleneck to be solved, also points to an installed capacity of only 3.5 GW of distributed energy, but discusses that investments in the sector, combined with more effective research, will increase production capacity in significant numbers, generating a reduction in distribution costs today.

The perspectives are very positive, although they encounter substantial challenges throughout the discussion, such as the impacts caused on populations in the global south by mineral extraction to seek a low-carbon transition (MATANZIMA et al., 2024), and the

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changes caused in socio-ecologically dependent peoples on extractivism (TUNN et al., 2024), among other points that need further scientific and technological deepening.

BOOSTING GREEN HYDROGEN IN THE WORLD

Decarbonization programs in industries, driven by pressures to reduce greenhouse gas emissions (Vogl et al, 2020), will only be fully viable with the emergence of a new market configuration for investment in green industrial products. Among the various tools available, Advance Purchase Agreements (AAC) and Contracts for Difference (CpD) stand out as fundamental mechanisms to foster the development of green hydrogen globally.

AAC's ensure the future purchase of products under development, encouraging emerging low-carbon technologies, while CpD's compensate for the difference between the combined price and the market price, ensuring a price guarantee for manufacturers. Both tools, usually subsidized by government entities, are essential to stimulate the reduction of carbon emissions.

Among the programs that use these agreements are active initiatives, such as the implementation of policies in France for investment of €4 billion in the production of low-carbon hydrogen (Carbon Contracts for Difference program), as well as proposals such as the US to provide US$ 1 billion for various demand mechanisms to hydrogen producers, including pay-per-delivery (DOE-OCED Regional Clean Hydrogen Hubs) and EU for the production of green hydrogen as a fuel in various industries, covering heavy industries such as steel and cement (REpowerEU Plan).

The World Resources Institute (GANGOTRA et. al, 2023) in an article on the subject clearly details the main solutions to overcome bottlenecks in the implementation of these contracts, whether through the promotion of consultations between stakeholders, seeking to establish clear pricing agreements and ensure budget and schedule predictability, or adopting regulatory reports and standards, launching platforms that connect the interests of buyers and sellers, and the development of pilot programs. Above all, it is necessary to learn from previous experiences, not only in other sectors and governments, but also in the project itself, so as not to insist on errors that could compromise the effectiveness of these policies.

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DISCUSSIONS

The main information contained in Figure 1 points to the interest aroused by the theme of green hydrogen as a source of research, there is a good number of international citations, an annual growth in searches for the theme in the order of 128% per year, with an average age per document investigated by the Bibliometrix of 1.64 years. Tables 2 and 3 respectively present studies published from 2019 to 2025 and the main journals with their respective publications mainly addressing renewable energy, energy production, energy and conservation.

A trend that follows in Figures 2 and 3 when the word cloud of the most used authors and the clusters formed from these words are presented, as shown in Figure 4, where the clusters formed point to decarbonization, chemical electrolysis, production of hydrogen, carbon and hydrogen.

International cooperation is well demonstrated in Figures 5 and 6, being relevant for researchers and their affiliations, although this statistical analysis did not present verifications of production costs, distribution costs, production yield and decarbonization potential, which is also a subject of low approach verified through the data selected in this study.

This gap was left open by the bibliometric analysis, although the report generated by biblioshiny is vast in information such as: the impact of publications at national and international level, the cloud of keywords used, the thematic map, the primary and secondary clusters generated that would greatly increase the amount of information in this study, even so it is understood in the end that further studies need to be carried out to complement these answers that remain open. As well as the bibliometric analysis of the articles selected for this study also left open the environmental cost of implementing the production of green hydrogen due to its high energy consumption by multi-electrolyzers, although in a complementary analysis it was observed that there is already a movement among researchers to seek alternatives to feed electrolyzers with alternating wind and photovoltaic to stabilize the supply current of the equipment and mathematical predictive studies also for this purpose.

Complementary analysis, with research carried out and detailed previously in the methodology, showed a more improved global perspective at the level of production and distribution, including a well-structured network through advance purchase agreements and contracts for difference, which are compensatory mechanisms already existing in the

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market, showing that the energy market is in parallel with scientific research driving the production of the fuel at a global level.

FINAL CONSIDERATIONS

The bibliometric analysis of the studies surveyed here and organized through the bibliometrix data package and its biblioshiny graphic environment were able to trace important points in the current progress of scientific research on this current and relevant topic from the socioeconomic point of view.

Although it is not a totally unknown energy proposal, the alternative of green hydrogen as an energy source of probable replacement to the existing matrix is current, necessary and has research throughout the planet for its effective viability. Its consolidation is not presented as a desire, but as a necessity, although bottlenecks and gaps such as pricing, distribution, and commercialization still need to be answered by managers, investors, and researchers.

The technological costs are high, the environmental costs also need to be better investigated, analyzed and improved. It is notorious that the technology used in production will implement a new milestone in energy and environmental supply with its perspective of decarbonization.

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