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Article

Green Hydrogen Economy and Sustainable Development: a Research Agenda Based on Bibliometrics of Scopus Data

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ABSTRACT

The objective of the study was to map the scientific production on the Green Hydrogen Economy and propose a research agenda for the field of Management from the perspective of Sustainable Development. The research is characterized as a quantitative study, using the bibliometric method. In the survey of publications, in August 2023, the terms 'Green hydrogen' and 'Economy' were searched for in the title, keywords and abstracts of the publications, identifying 469 publications, which correspond to the sample of the present study. The analysis was carried out using the bibliometric methods presented by Zupic and Cater (2015), using the VOSviewer software, version 1.6.17. There was an exponential growth in publications on the topic from 2019 onwards, with a predominance of publications by researchers from China, Germany and the United States. It is worth noting that the USA and China are the most polluting countries in the world, and Germany has been among the countries that lead investments in H2V. The growing adhesion of new countries and researchers has structured a thriving network of relationships, citations and co-production of knowledge. However, research is still restricted to technical issues and small-scale experiments. There is a gap in the congruence of studies relating H2V and Management. Although the technical solutions to enable the production and distribution of H2V in the domestic and international markets come essentially from areas such as engineering, energy and the environment, the study of management throughout the H2V value chain is essential to support research on the H2V Economy from the perspective of sustainable development. The main topics for the agenda of future studies are to delve deeper into the other dimensions of Sachs' sustainability, in addition to the environmental dimension. Management should also be considered from the perspective of sustainable development, extending the research to areas such as technology, marketing, global value chain and international business.

Keywords: sustainable development; management; bibliometric mapping; Scopus.

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RESUMO

O objetivo do estudo consistiu em mapear a produção científica sobre Economia do Hidrogênio Verde e propor agenda de pesquisa para o campo de Gestão na perspectiva do Desenvolvimento Sustentável. A pesquisa caracteriza-se como um estudo quantitativo, por meio do método bibliométrico. No levantamento das publicações, em agosto de 2023, buscaram-se os termos 'Green hydrogen' and 'Economy', no título, palavras-chave e resumos das publicações, identificando-se 469 publicações, que correspondem à amostra do presente estudo. A análise foi realizada a partir dos métodos bibliométricos apresentados por Zupic e Cater (2015), com o software VOSviewer, versão 1.6.17. Verificou-se crescimento exponencial nas publicações sobre o tema a partir de 2019 e predominância de publicações de pesquisadores da China, Alemanha e Estados Unidos. Destaca-se que EUA e China são os países mais poluentes no mundo e a Alenhanha tem estado entre os países que lideram os investimentos em H2V. A adesão crescente de novos países e pesquisadores estruturou uma pujante rede de relações, citações e coproduções de conhecimento. Entretanto, as pesquisas ainda se restringem a questões técnicas e experimentos de pequena escala. Há uma lacuna quanto à conguência dos estudos relacionando H2V e Gestão. Apesar das soluções técnicas para se viabilizar a produção e distribuição de H2V nos mercados doméstico e internacional serem essencialmente oriundas de áreas como as engenharias, energia e meio ambiente, o estudo da gestão ao longo da cadeia de valor do H2V é essencial para dar suporte a pesquisas sobre Economia do H2V na perspectiva do Desenvolvimento sustentável. Como principais temas para agenda de estudos futuros propõem-se aprofundar as demais dimensões da sustentabilidade de Sachs, para além da dimensão ambiental. Também considerar a gestão na perspectiva do Desenvolvimento sustentável, estendendo a pesquisa para áreas como Tecnologia, Marketing, Cadeia Global de Valor e Negócios internacionais.
Palavras-chave: desenvolvimento sustentável; gestão; mapeamento bibliométrico; Scopus.

Introduction

Energy is an important pillar of life in society, and the search for sustainable sources is essential for the competitive advantage of organizations and nations (Goldemberg & Lucon, 2007) and for sustainable development (Romano, 2014), considering the mitigation of important environmental problems, such as global warming, droughts and floods (Blank, 2015). As a result, the search for renewable energy sources is on the global policy agenda, endorsed by the Paris Agreement, signed by Brazil and other countries, with a commitment to reduce carbon emissions by 2050 (Onubr, 2021), and is also a recurring theme in the academic and business fields (Mascarenhas & Weersma, 2017).

Green hydrogen (H2V), from renewable sources, represents a vast, storable and decarbonized energy strategy (Erbach & Jensen, 2021; Elkerbout et al. 2020; Yu et al. 2021). Europe, for example, aims to become climate neutral by 2050, with hydrogen energy technology supplying up to 14% of continental demand; today, this percentage is less than 2% (Erbach & Jensen, 2021; Elkerbout et al. 2020). The US Department of Energy is working to reduce the cost of producing hydrogen by 80% in a decade (Energy.Gov, 2021).

Governments and private companies are progressively investing resources in the development of hydrogen technologies, but there are still technical challenges, economic and geopolitical implications (Noussan et al. 2021; Saygin; Gielen, 2021; Wanner, 2021; Yu et al. 2022). As a result, hydrogen has still been extracted mainly from coal and natural gas, sources of fossil origin, which increase the impact on climate change (Beswick et al. 2019; IEA, 2019). According to the International Energy Agency (IEA, 2019), less than 0.7% of current hydrogen production comes from renewable or fossil fuel sources in plants equipped to capture the carbon emitted.

Energy crises demand investments in transitioning to renewable energy sources, as shown by Chien et al. (2021) Gondal, Masood and Khan (2018) and Xu et al. (2019), in an analysis of Pakistan's energy crisis, and Andrade Guerra et al. (2015), in pointing out that the Brazilian energy scenario reflects shortages in the medium and long term. As an alternative, H2V contributes to global warming, environmental protection and transindividual and intergenerational fundamental rights (Lenza, 2020). By expanding the topic, research can contribute to analyses of the environment and dignified life as rights expressed in the 1988 Federal Constitution, articles 225 and 170, as well as business opportunities and job creation, to boost the economy through the possibilities of added economic and social development.

It is therefore considered that expanding the supply of renewable energy is a contributory factor to development, with gains related to human labor (Sachs, 2012). In this way, H2V can be referred to as sustainable development, considering social, environmental and economic contributions, among other development possibilities, such as political, cultural and territorial (Sachs, 2009), arising from decarbonization, based on efficient and sustainable energy resources (Koneczma, 2021). The impact of green hydrogen on sustainable development in its most diverse aspects led to the research question: how is scientific production on the Green Hydrogen Economy characterized? To this end, the aim of the study was to map scientific production on the Green Hydrogen Economy and propose a research agenda for the field of Management from the perspective of Sustainable Development. In this way, this work seeks to contribute to the scientific production of this field, identifying the most addressed topics and the research gaps in the literature.

The research's contributions, therefore, go hand in hand with the development of policies, programs and projects related to the use of H2V from the perspective of the energy transition, as suggested by Lee and Kim (2021), Perez, Brent and Hinkley (2021), in which H2V Management needs to take place from the perspective of Sustainable Development to be effective. The mapping brings together information on the subject from a broad scope of analysis, with information on researchers, themes and theoretical-empirical relationships on the H2V economy, which provides insights into the research agenda and expands the repertoire for tackling the associated challenges.

Green hydrogen economy

Green hydrogen (H2V) plays a potentially valuable role in future energy production (IEA, 2019; Noussan et al. 2021; Saygin & Gielen, 2021). In recent decades, there has been more research into the production of hydrogen from various sources, transporting it, storing it and using it to provide final energy services without emissions, with repercussions in the political and business spheres for this energy source (IEA, 2019; Saygin & Gielen, 2021).

Hydrogen generation technologies are classified according to a spectrum of colors: gray (can also be brown or black) produced by fossil fuel, which causes carbon dioxide emissions; blue, by combining gray with carbon capture and storage and avoiding greenhouse gas emissions; turquoise, by pyrolysis of a fossil fuel in which the by-product is solid carbon; green, when produced by electrolyzers supplied by renewable electricity or other bioenergy-based pathways; yellow (or purple), produced by electrolyzers powered by electricity from nuclear power plants (Newborough & Cooley, 2020; Noussan et al. 2021).

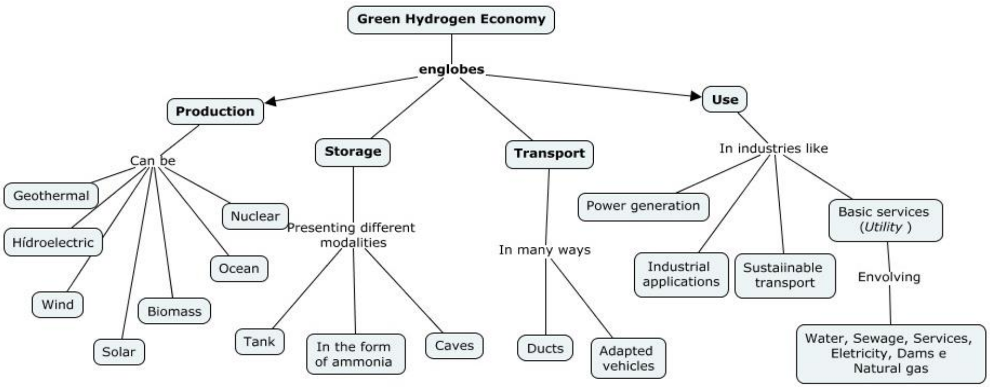
In countries that adopt power-to-gas conversion, hydrogen has been considered a promising material that can be used immediately, stored indefinitely for later use or transported over long distances (Gondal, 2018; Hinkley, 2021; Walker; Fowler & Ahmadi, 2015; Wanner, 2021). The scale of H2V production can be centralized in large plants or can be done on a small scale, in a distributed manner, to meet localized demands. It can also be implemented offshore, over water, using green energy from sources such as wind or solar power. Technologies to improve generation efficiency, such as hydrolysis combined with water desalination, catalysts and biomass production have been addressed in studies (Beswick, Oliveira & Yan, 2019; Zhang et al. 2020).

Storing large quantities of H2V involves technical challenges and specific technologies, but mitigates the problem of unstable supply from wind and solar sources, and the limitations of lithium batteries (Erbach; Jensen, 2021; Wanner, 2021). It can be done in tanks designed for this purpose, or in caverns adapted to receive and store the gas (Capurso et al., 2022; Jastrzębski & Kula, 2021; Winkler-Goldstein & Rastetter, 2013). The use of high-efficiency compressors allows for a reduction in volume and better use of storage space (Wanner, 2021). If H2V needs to be transported over long distances, it is usually stored in the form of ammonia or liquid hydrogen (Capurso et al. 2022; Hinkley, 2021).

The hydrogen produced needs efficient distribution networks to ensure that demand is met in a timely manner, even if it is far from the point of generation. In this case, pipelines are a viable option and can operate continuously if necessary (Wanner, 2021). Transportation by land, sea or air can be done by vehicles adapted with high-capacity liquid hydrogen or ammonia storage tanks (Hinkley, 2021).

Possible applications for H2V are varied. Energy generation is promising, due to its reduced environmental impact and the possibility of storing it as hydrogen or methanol obtained from green hydrogen (Saygin & Gielen, 2021). In the industrial sphere, for example, it can be used to decarbonize processes, as well as to produce fertilizers, plastics or fibres. Physical spaces and transport (for people and cargo) can also be sustainably powered using this source (Kotze et al. 2021; Perez, Brent & Hinkley, 2021). Figure 1 shows the sectoral developments of the green hydrogen economy.

Figure 1: Development in the Green Hydrogen Economy.



Source: Adapted from Beswick, Oliveira & Yan (2019), Zhang et al. (2020), Perez, Brent & Hinkley (2021), Wanner (2021), Clark II & Rifkin (2006) and Noussan et al. (2021).

Considering the unfolding of the H2V Economy (Figure 1), there are challenges to integrating the various links in the green hydrogen economy (Hinkley, 2021; Wanner, 2021). To this end, it is important to engage government and business to finance the development of technologies and gains in scale (Perez, Brent & Hinkley, 2021), to contribute to the management of the integration process that allows for agility in the flow of production, storage, transportation and use of H2V.

Also, according to Albrecht et al. (2020), the development of the Green Hydrogen Economy is at different stages globally, considering that each region has different objectives and motivations in this context, as can be seen in figure 2:

Figure 2: Stage of development of the Hydrogen Economy in the World

Source: Albrecht et al., (2020).

Figure 2 shows that, despite the differences in the level of development of the Hydrogen Economy in the regions, related to the motivations and particularities of each region, there is a global consensus that hydrogen is an essential component towards a low carbon economy. As such, the outlook is that domestic strategies will be developed and improved by countries by 2025 (Albrecht et al. 2020).

Methodology

Quantitative research uses bibliometric methods, considering quantitative aspects of the production, dissemination and use of recorded information (Macias-Chapula, 1998). According to Zupic & Cater (2015), bibliometric studies can include citation analysis, co-citation analysis, bibliographic coupling, co-authorship analysis and keyword networks.

To survey the publications analyzed in the study, the Scopus database, belonging to the Elselvier company, was chosen, as it is considered to be the largest database of abstracts and citations of literature in the world, with an interdisciplinary profile, integrating research in the areas of science, technology, health, social sciences, among others (Elsevier, 2023). As well as being a database, the Scopus platform also offers tools for presenting data, making it easier to visualize research.

For the survey in August 2023, the terms 'Green Hydrogen Economy' were considered in the title, abstract and keywords, but only 54 publications were found. A new survey using the terms 'Green hydrogen' with the Boolean marker AND the term 'Economy' found 469 documents, all of which were considered in this study. They were analyzed from the first publication on the terms 'Green Hydrogen' and 'Economy', indexed in Scopus, until August 2023.

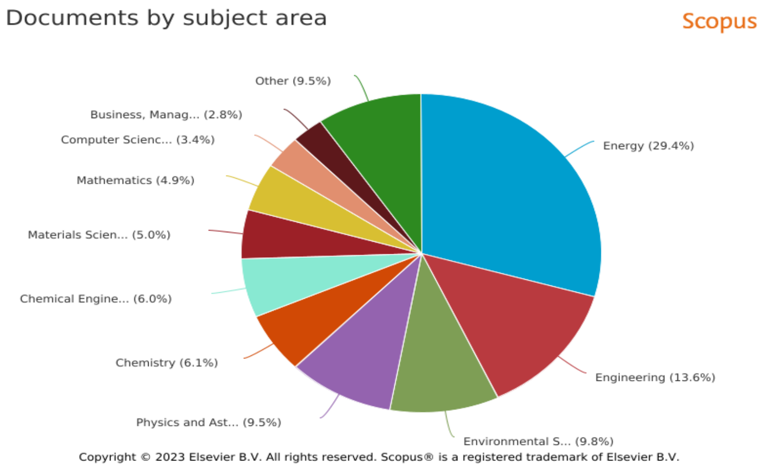
The data was processed using the VOSviewer software, version 1.6.17, a tool for building and visualizing bibliometric networks that allows data to be imported from the Scopus database, among other databases. The software identifies networks formed by journals, authors and countries, which are based on citations, bibliographic coupling, co-citations or co-authorship relationships (VOSviewer, 2021).

Co-citation analysis helps to identify networks through the frequency with which authors are referenced together. In this way, citations and co-citations form one of the bases of linkage indicators, represented graphically through social networks (Oliveira & Grácio, 2012). Bibliographic linkage indicates the list of references that tend to be repeated in articles in a given area, and can be based on authors, documents or journals. Coauthorship analysis also indicates which authors are usually cited together in the publications analyzed, and keyword analysis connects them to each other and to terms used in the title and abstract (Zupic & Cater, 2015).

Results

The 469 articles indexed in Scopus are distributed in 20 categories previously defined by the Scopus platform with their respective numbers, as shown in Figure 3: Energy (303), Engineering (140), Environmental Science (101), Physics and Astronomy (98), Chemistry (63), Chemical Engineering (62), Material Sciences (51), Mathematics (51), Computer Science (35), Social Sciences (29), Business, Management and Accounting (29), Earth and Planetary Sciences (22), Economics, Econometrics and Finance (18), Biochemistry, Genetics and Molecular Biology (8), Multidisciplinary (6), Decision Sciences (5), Arts and Humanities (4), Medicine (3), Agricultural and Biological Sciences (1) and Psychology (1). The Business, Management and Accounting category ranks 10th in the order of research areas with 29 publications, along with the Social Sciences area. This field of research, however, is essential to support further research into the Green Hydrogen Economy from the perspective of Sustainable Development.

Figure 3: Study areas of the Green Hydrogen AND Economy publications on Scopus.

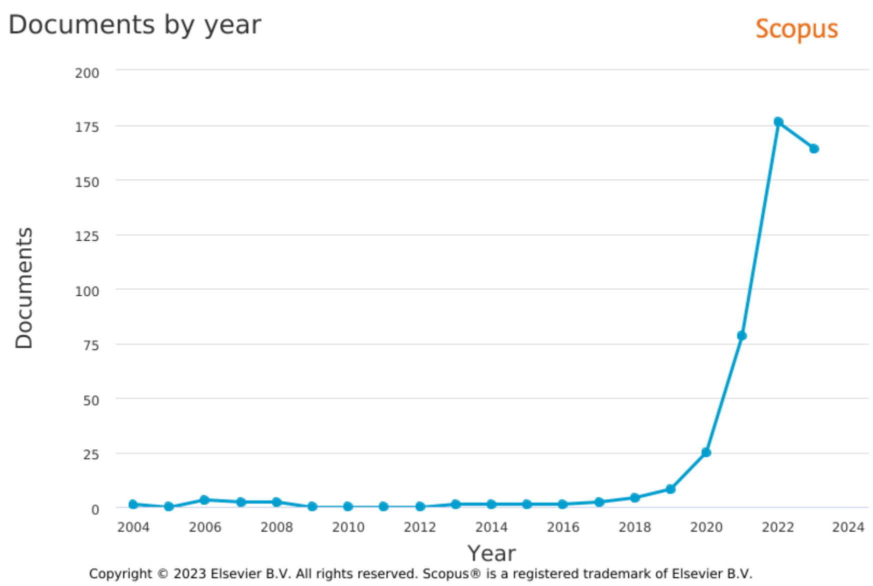


Source: Scopus (2023).

Figure 3 shows that the subject under study covers an interdisciplinary scope, albeit to a greater extent for studies related to energy. The illustration also shows that the area of management has a small share of the articles selected, which indicates gaps in studies in this area and many possibilities for contributions in future studies linking the Green Hydrogen Economy, Management and Sustainable Development. Based on the texts selected, the most referenced journals were: International Journal of Hydrogen Energy (68), Energies (33), Energy Conversion and Management (20), Sustainability Switzerland (13), Chemical Engineering Journal (8) and Journal of Cleaner Production (8).

As for the evolution of publications over time, the oldest publications in the Scopus database date back to 2004 and 2006. However, in 2004 only a two-page bulletin was published, with no identification of the author. In 2005, no publications on the subject were indexed in Scopus and only in 2006 were the studies by Clark II & Rifkin (2006) & Parkinson (2006) published. This was followed by publications by Smith (2007), Clark (2007) and Clark II (2008). The evolution of publications in this period can be seen in Figure 4.

Figure 4: Evolution of publications and citations on 'Green Hydrogen' AND 'Economy'.



Source: Scopus (2023).

Among the 469 articles, there were no publications between 2009 and 2012 and in 2013, 2015, 2016 and 2017 there was only one production per year, respectively the works of Winkler-Goldstein and Rastetter (2013), Walker, Fowler and Ahmadi (2015), Moustafa et al. (2016) and Camacho et al. (2017). In 2019, the volume of articles increased, with significant growth in 2021 and 2022, showing an increase in interest from researchers on the subject, with a total of 78 publications in 2021, 176 in 2022 and in August 2023, 164 publications were already identified, reaching almost the total number of publications in 2022. The increase in publications from 2019 onwards may have been motivated by the Paris Agreement and the environmental crisis, among other international factors.

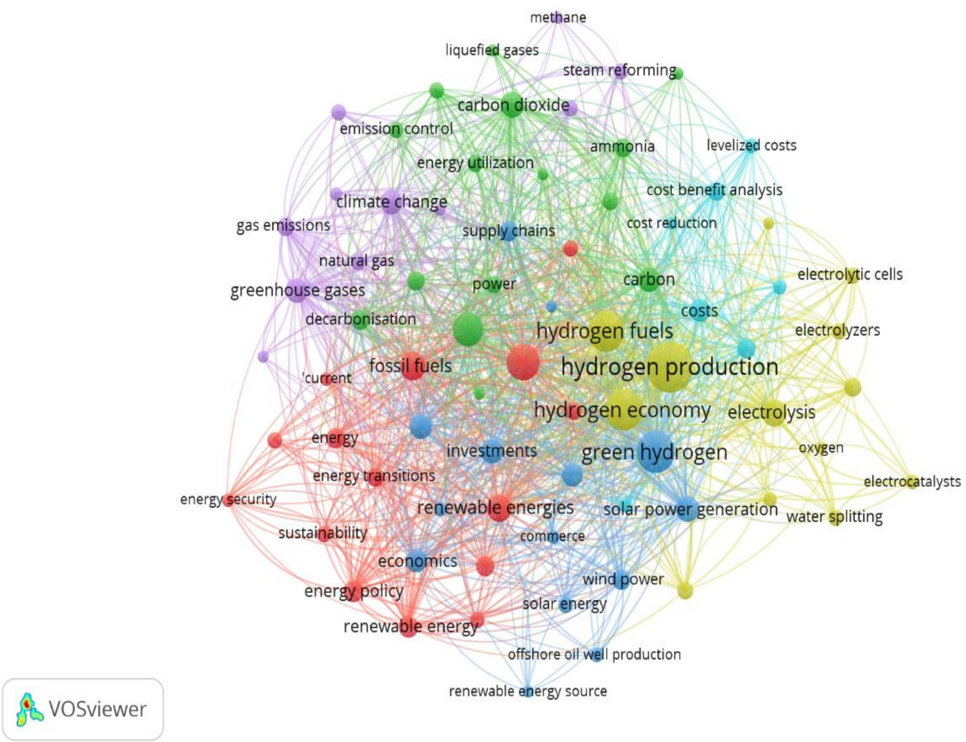
When checking the co-occurrence of keywords in the 469 articles, a total of 3458 keywords were found, 97 of which had at least 10 occurrences, which were distributed in 5 clusters, with a total link strength of 12,542 and 3,145 links. Figure 5 shows the clusters with the distribution and connection of the keywords.

The blue cluster comprises the keywords: alternative energy, biomass, blue hydrogen, carbon dioxide, circular economy, energy, energy security, energy policy, energy transition, environmental impact, fossil fuels, global energy, green economy, green hydrogen, hydrogen, renewable energies, renewable energies, sustainability, and sustainable development.

The green cluster is made up of the keywords: clean energy, trade, economics, electrical energy storage, electrolysers, energy management, energy storage, energy systems, hydrogen storage, investments, natural gas, offshore oil well production, energy, power-to-x, renewable energy resources, solar energy, solar energy production and wind energy.

The red cluster has the following keywords: a-carbon, ammonia, carbon, carbon capture, carbon dioxide, carbon neutral, chemical analysis, CO_2 emissions, coal industry, cost-benefit analysis, cost reduction, costs, economic analysis, emissions control, energy carriers, energy efficiency, energy use, fuel economy, global warming, hydrogen supply chains, levelized costs and life cycle.

Figure 5: VOSviewer output with the thematic network of co-occurring keywords



Source: Research data (2023).

The keywords are distributed in descending order in terms of total link strength, followed by total occurrences. The 20 keywords with the highest occurrences and total link strength were: hydrogen production

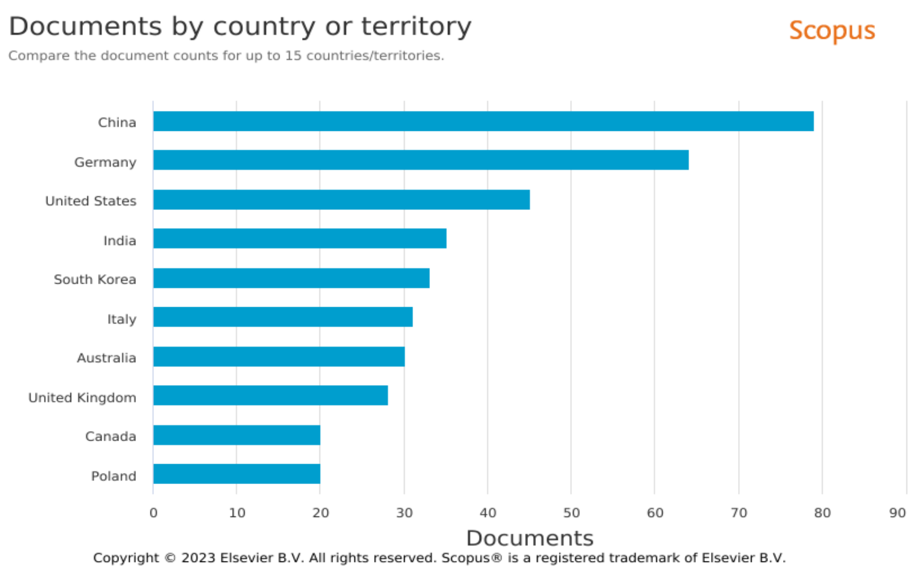
(216 total link strength and 1720 occurrences), hydrogen fuels (129 and 1044), hydrogen economy (137 and 984), green hydrogen (145 and 978), hydrogen storage (91 and 812), hydrogen (114 and 749), fossil fuels (64 and 584), renewable energies (58 and 548), greenhouse gases (48 and 495), solar power generation (55 and 494), electrolysis (60 and 485), renewable energy resources (52 and 476), carbon dioxide (55 and 456), investments (49 and 424), climate change (50 and 406), carbon (46 and 395) renewable energy (44 and 371), fuel cells (44 and 371), decarbonization (37 and 362) and costs (42 and 349).

Hydrogen production is the most prominent issue across the keyword network. This is because it is still one of the most difficult challenges for the green Hydrogen Economy: how to produce Hydrogen in a spotless way and make its transport and commercialization viable to promote sustainable development by reducing greenhouse gases, optimizing natural resources and establishing a sustainable energy transition.

Around production, other terms that were also referenced a lot were hydrogen economy, green hydrogen, hydrogen stock, fossil fuels. Renewable energies, greenhouse gases, solar power generation, carbon dioxide, investments, decarbonization, climate change and costs. The high level of investment and costs involved in the production of H2V, as well as the production process linked to sustainable energy sources such as solar energy, are still a challenge for organizations and countries, so that they can structure and carry out the energy transition that the planet needs and balance organizational and governmental interests with the warnings of international bodies and what was established in the Paris Agreement (Jastrzębski & Kula, 2021; Capurso et al. 2022).

The 469 articles were published by researchers from 73 countries. Figure 6 shows the ranking of the 10 countries with the highest number of publications, with China leading the ranking (79 publications), followed by Germany (64) and the United States (45).

Figure 6: Publications on ‘Green Hydrogen’ and ‘Economy’ by country

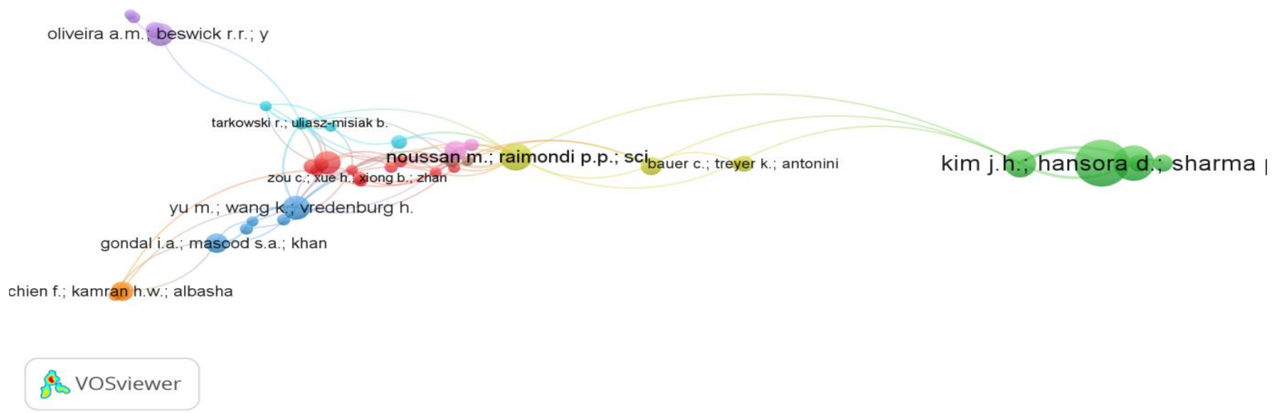


Source: Scopus (2023).

Figure 6 shows that the countries with the highest volume of research on “Green Hydrogen” AND “Economy” come from Asia, Europe and North America. South America, Central America and Africa were inexpressive in academic production on the subject, corroborating Albrecht et al. (2020) in which these countries occupy the first places in the timeline of publications of national green hydrogen strategies, and the global stage of the Green Hydrogen Economy is led by regions of the European Union and Japan, motivated by issues related to energy security.

Despite this, as countries seek to comply with the Paris Agreement, European countries such as Germany and France, which do not have the geographical and territorial conditions to meet the Agreement's requirements, have been looking to countries in South America, Central America and Africa for partnership opportunities to enable their economies to adapt to the reduction of pollutants in the energy transition from renewable energies. However, in addition to providing resources and a favorable environment for the production of H2V in partner countries, these countries also need to advance in the study of H2V to strategically define how they will position themselves in relation to other countries that are at a higher level of economic development. The bibliographic coupling network per article is shown in Figure 7.

Figure 7: VOSviewer output with bibliographic coupling network per article.



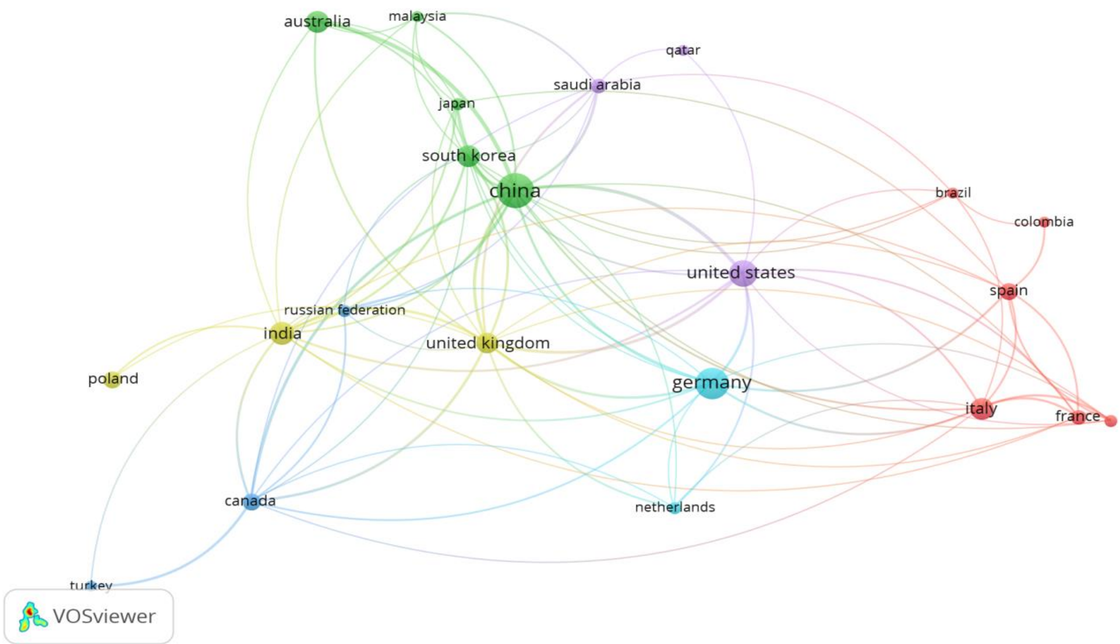
Source: Research data (2023).

With at least 30 citations per article, a total of 40 works were identified with a total link strength of 148, distributed in 9 clusters and 95 links:

- Cluster 1 (red) is made up of the authors: Al-Othman et al. (2022), Benalcazar and Komorowska (2022), Capurso et al. (2022), Hoelzen (2022), Jorschick et al. (2021), Kazi et al. (2021), Okonkwo et al. (2021), Rambhujun et al. (2020), Trattner, Klell & Radner (2022), Zou et at. (2021a, 2021b).
- Cluster 2 (green) shows the relationship between the authors: Kim et al. (2019), Li et al. (2021), Yang (2021), Yu, Budiyanto & Tuysuz (2022) and Zhang et al. (2020).
- Cluster 3 (dark blue) shows the relationship between the authors: Barhoumiet al. (2022), Gondal, Masood & Khan (2018), Thapa et al. (2021), Yu, Wang & Vredenburg (2021);
- Cluster 4 (yellow) highlights the relationship between Bauer (2022), Megia et al. (2021), Noussan et al. (2021) and Wang et al. (2021);
- Cluster 5 (lilac) shows the relationship between Clark II and Rifkin (2006), Dong et al. (2022), Oliveira, Beswick & Yan (2021) and Saygin & Gielen (2021).
- Cluster 6 (light blue) includes the relationship between the studies by the authors: Cloete, Runau & Hirh (2021), Hunt et al. (2022), Li & Taghizadeh-Hesary, 2022) and Zhao et al. (2022).
- Cluster 7 (orange) is made up of work by Chien et al. (2021), Xu et al. (2019) and Zhao et al. (2022).
- Cluster 8 (beige) shows the relationship between the works of Field and Derwent (2021) and Liu, Xiong & Gao (2022).
- Finally, Cluster 9 (lilac) shows the relationship between the articles by Mac Dowell et al. (2021) and Yates et al. (2020).

Regarding co-authorship by country, there were a total of 79 countries, 22 of which had at least 7 published articles cited at least once. The co-authorship network by country had a total link strength of 183, in which the 22 countries are distributed in 6 clusters and have 90 links, as shown in Figure 8.

Figure 8: VOSviewer output with the co-authorship network by country.



Source: Research data (2023).

Figure 8 shows the six clusters with the distribution of co-authorship by country. Thus, the red cluster is made up of the following countries: Brazil, Colombia, France, Italy, Norway and Spain; the green cluster is made up of Australia, China, Japan, Malaysia and South Korea; the dark blue cluster includes Canada, Russia and Turkey; the yellow cluster is made up of India, Poland and the United Kingdom; the lilac cluster includes Qatar, Saudi Arabia and the United States and, finally, the light blue cluster includes Germany and the Netherlands. The clusters identified show the concentration of knowledge production on H2V economics.

The descending order of total link strength by country has the following characteristics: China (52 total link strength, 1927 citations and 79 publications), United Kingdom (39, 362, 28), United States (31, 752, 46), Germany (27, 1105, 64), India (27, 240, 35), Canada (25, 451, 20), South Korea (22, 786, 33), Italy (19, 554, 31), Australia (16, 451, 30), France (14, 101, 14), Saudi Arabia (14, 238, 15), Spain (14, 135, 20), Norway (13, 89, 10), Japan (10, 234, 11), Russia (9, 103, 11), Malaysia (8, 123, 8), Netherlands (8, 195, 10), Brazil (6, 89, 8), Turkey (5, 62, 9), Colombia (3, 21, 8), Poland (3, 151, 20) and Qatar (2, 166, 9).

In addition to the distribution of publications on Green Hydrogen and Economy in the Scopus database by area of knowledge, the evolution of publications over the years, the co-occurrence of keywords, the distribution of publications by country, the bibliographic coupling network per article and the co-citation by country, we also presented the ranking of the most cited publications in the Scopus database, in descending order and with more than 100 citations, considering the research data, as illustrated in Table 1.

The economic crisis of 2008 seems to have influenced the sustainability movement (Geels, 2013), with a possible impact on productions related to the topic in subsequent years. Noussan et al. (2021), for example, deal with the H2V economy in the post-crisis period of 2008, highlighting advances in technologies that favor the growth of H2V consumption and production, in a transition to a zero-carbon economy to be realized in the coming decades. They also reinforce geopolitical opportunities for trade between producing and consuming countries, as well as projections of reduced production costs, increased consumption in countries and the expansion of hydrogen-powered vehicles.

Kim et al. (2019) discuss the challenges and variations of H2V production using solar energy through photocatalytic (PC), photoelectrochemical (PEC) and photovoltaic-electrolysis (PV-EC) processes. The need to gain scale is highlighted by the authors with the metaphor of "an artificial photosynthetic challenge from a leaf to a forest".

The work by Zhang et al. (2020) addresses the technology of electrocatalysts for water electrolysis, which demands more efficiency and cost-effectiveness. The research identified technical challenges that would have to be overcome over the course of a decade before the technology could become an effective option for commercial applications. The research by Yu, Budiyanto & Tüysüz (2022) also looks at electrolysis technologies, with an emphasis on catalysts that use more readily available materials.

The economic crisis of 2008 seems to have influenced the sustainability movement (Geels, 2013), with a possible impact on productions related to the topic in subsequent years. Noussan et al. (2021), for example, deal with the H2V economy in the post-crisis period of 2008, highlighting advances in technologies that favor the growth of H2V consumption and production, in a transition to a zero-carbon economy to be realized in the coming decades. They also reinforce geopolitical opportunities for trade between producing and consuming countries, as well as projections of reduced production costs, increased consumption in countries and the expansion of hydrogen-powered vehicles.

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Table 1: Ranking of the most cited articles on Green Hydrogen Economics.

Article title	Authors	Year	Journal	Cit.
Toward practical solar hydrogen production-an artificial photosynthetic leaf-to-farm challenge	Kim, J. H. et al.	2019	Chemical Society Reviews	606
Bifunctional Heterostructured Transition Metal Phosphides for Efficient Electrochemical Water Splitting	Zhang, H. et al.	2020	Advanced Functional Materials	345
Principles of Water Electrolysis and Recent Progress in Cobalt-, Nickel-, and Iron-based Oxides for the Oxygen Evolution Reaction	Yu, M., Budiyanto, E., Tüysüz, H.	2022	Angewndte Chemie	221
The role of green and blue hydrogen in the energy transition-a technological and geopolitical perspective	Noussan, M. et al.	2021	Sustainability (Switzerland)	204
Insights into low-carbon hydrogen production methods: green, blue and aqua hydrogen	Yu, M. Wang, K., Vredenburg, H.	2021	International Journal of Hydrogen Energy	166
Rationally designed indium oxide catalysts for CO2 hydrogenation to methanol with high activity and selectivity	Dang, S. et al.	2020	Science Advances	155
Perspective of the role of Hydrogen in the 21st century energy transition	Capurso, T. et al.	2022	Energy Conversion	147
A Green Hydrogen Economy for a renewable energy society	Oliveira, A.M., Beswick, R.R., Yan, Y.	2021	Current Opinion in Chemical Engineering, 33, 100701	142
Green hydrogen production potential for developing a hydrogen economy in Pakistan	Gondal, I.A., Masood, S.A., Khan, R.	2018	International Journal of Hydrogen Energy	113
Dynamic planning, conversion, and management strategy of different renewable energy sources: A Sustainable Solution for Severe Energy Crises in Emerging Economies	Chien, F., Yang, F. et al.	2021	International Journal of Hydrogen Energy	112
Techno-economic analysis of green hydrogen production from biogas autothermal reforming	Camacho, Y.S. M. et al.	2017	Clean Technologies and Environmental Policy	110

Source: Adapted from Scopus (2023).

Note: Cit.: Total citations

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Noussan et al. (2021) address the issue of green and blue hydrogen production using a technological and geopolitical approach. The authors emphasize that the transition to the use of sustainable, zero-carbon energy faces challenges such as the transparency of indicator standards, standards and targets. Fighting climate change in a divided world, where national standards and objectives are not integrated into a global approach, can increase inequalities between countries (Noussan et al. 2021).

The search for more economical and carbon-free generation technologies motivated the work of Yu, Wang & Vredenburg (2021). The authors propose an alternative method of generating hydrogen, intermediate between green and blue hydrogen, based on oil sands saturated with natural bitumen, ‘Aqua hydrogen’. This technology is still in the development stage, requiring investment and gains in scale, as well as greater dissemination and sustainability studies.

Dang et al. (2020) sought to develop better catalysts to produce methanol using hydrogen obtained from sustainable sources to capture carbon. The scientists presented comparative tests of different catalysts, regarding their temporal performance, in an experimental environment.

Capurso et al. (2022) describe hydrogen generation technologies and analyze their efficiency, considering generation, transportation, storage and use. The authors identify that in certain cases, generation is not entirely sustainable and that in other situations, the use of hydrogen is less efficient than other technologies, such as in vehicle mobility using lithium batteries.

The text by Oliveira, Beswick & Yan (2021) deals with the issue of the green hydrogen economy, presenting an optimistic point of view, but based on indicators. The authors present green hydrogen as important for decarbonizing sectors that don't have green alternatives. The research identifies that hydrogen will increase its share as an industrial raw material and in the construction, energy and transportation sectors.

Gondal, Masood & Khan (2018) portray Pakistan as a country in an energy crisis, struggling to maintain its energy supply and contain the growth in demand. In this scenario, H2V is characterized as an alternative to take advantage of the country’s generation potential. The text highlights the capacity to generate energy from available renewable sources, denoting that renewable energy generation based on biomass hydrogen and solar energy would be the most promising alternatives for developing the green hydrogen economy in the country.

The research by Chien et al. (2021) complements that of Gondal, Masood & Khan (2018), and Xu et al. (2019) by addressing Pakistan's energy crisis and alternative ways of generating H2V as a potential solution to this issue. The authors strongly advocate the production of H2V through wind energy, one of the country's potentials, using a quantitative model. As alternative sources, the authors point to small hydroelectric plants and solar energy. There is therefore disagreement with the findings of Gondal, Masood & Khan (2018) and Xu et al. (2019) on the generation of green hydrogen energy in Pakistan, a controversy that must be taking place in several countries.

The research by Camacho et al. (2017) evaluates the financial viability of producing H2V from biogas (‘biogas-to-hydrogen’). The costs and amortizations over 10 years show that it would be possible to produce hydrogen at a much lower cost than the target value set by the European community of €5/kg of H2.

Discussion: Agenda for future studies

The progress of scientific publications on green hydrogen economics is evident and is being drawn from multiple sources. However, its interface with the area of sustainable development management is incipient and presents theoretical and empirical gaps that require attention. Simultaneously, to support research into H2V from a sustainable development perspective, an important research agenda is to study the analysis of green hydrogen as a sustainable innovation (Hansen, Grosse-Dunker & Reichwald, 2009), which includes expanding access to the energy source with regulations that enable policies, programs and projects that guarantee benefits to society.

There has also been a growing number of new countries and researchers who are structured in a thriving network of relationships, citations and co-productions of knowledge. However, much of the research focuses on technical issues and small-scale experiments. Some of the current scientific production is essentially aimed at supporting the implementation of small generation and distribution projects and competition between new technologies related to green hydrogen (Kim et al. 2019; Yu, Budiyanto & Tuysuz, 2022; Zhang et al. 2020).

In this context, future research agendas include the analysis of H2V and its management from the perspective of sustainable development, with the study of topics such as: the management of renewable sources; supply chains that use the input, identifying their participants and assessing their efficiency; the energy crisis and investments in renewable sources; energy and climate change; and energy efficiency. In the area of environmental sustainability, there are some theories that can be explored in the context of H2V, such as Strategic Environmental Assessment (SEA), the Triple Bottom Line (TPB), Environmental, Social and Governance (ESG), Green Theory, Ecodevelopment Theory, among others. In addition, considering that the production of H2V requires high investment in technology and innovation, studies are recommended that explore theories aimed at sustainable innovation such as the Triple Helix Theory, Quadruple Helix and Fivefold Helix, Systems Dynamics Theory, Dynamic Capabilities Theory, Sábato's Triangle and the National Innovation System (NIS).

Another question to be considered concerns understanding the aspects that have promoted the substantial increase in research into H2V since 2020. Was it due to the discussions on the Paris Agreement and the resulting energy transition? What are the social, economic, territorial, cultural, ecological, national and international political impacts?

In the field of Marketing, the study of consumer behavior, pro-environmental behavior and green consumers is indicated as a future research agenda, using theories such as the Theory of Planned Behavior (TPB) and the Theory of Reasoned Action (TAR) to establish the predictors that influence the behavior of individuals in the context of sustainable consumption.

In the field of International Business, we suggest investigating international competitiveness between countries in the production of H2V, the impacts generated by H2V in world rankings of international competitiveness, as well as H2V as an energy alternative in a context of crisis and energy dependence of nations, in addition to identifying the possible scenarios and dynamics of future global H2V policies in the world context and how H2V contributes to the evolution of the field of international business research.

Another issue to be considered from the perspective of international business is the prominence of China, Germany and USA in research on H2V economics. It is necessary to investigate what has generated the preponderance of publications from these three countries. Is it the level of public investment in science and research, a government strategy or an institutional characteristic of China, USA or Germany? In other words, we need to explore the reasons for this scenario of scientific distribution on H2V in these countries to understand the political-institutional dynamics of these countries that mobilize greater scientific production.

USA and China are the most polluting countries in the world. China has been changing its paradigm regarding sustainability and decarbonization agendas. This has been reflected in its strategic decisions and foreign policy priorities, in particular, in foreign direct investment flows and in the commitments made by China to the international community at the Conference of the Parties (Nunes et al. 2023).

The United States had been developing its energy transition policies, with the goal of reducing the country's emissions by 50-52% by 2030, taking 2005 as the base year and achieving emissions neutrality by 2050. To this end, the country had been establishing the most significant climate legislation in US history by 2024, making a substantial investment in climate action, promoting environmental justice and ensuring America's position as a world leader in domestic clean energy production (Lemos et al. 2024).

On the other hand, to investigate the inequality of scientific production between the continents, where there is no evidence of production by African researchers, it is possible that the process of economic development of the countries has an impact on the level of investment in research on H2V and sustainable development and impacts on the other dimensions of Sustainable Development such as the environmental and social.

In the field of public management, we propose research that analyzes government-company partnerships in the production of H2V, public policies and public management in the context of sustainable cities and Smart Cities. It is also important to understand, within the major H2V production projects, social participation within this process, including how society is being impacted, whether it is being heard and how it perceives these impacts daily. Furthermore, in addition to understanding the framework of regulations aimed at regulating H2V, research is needed into how punitive laws for violations of environmental preservation will have an impact on local businesses and the surrounding population.

It is necessary to carry out research on the adoption of hydrogen in practical terms, considering the production scales demanded by reality, covering the human aspect of the sociotechnical ecosystem of green hydrogen and promoting efficient cooperative actions (Chien et al., 2021; Noussan et al. 2021). A critical approach to practical cases is recommended, listing the real benefits of H2V, detailed cost analyzes and the identification and exploration of risks related to the subject of green hydrogen, to further qualify current research.

Finally, we also suggest issues related to social licenses, the permission of communities to operate H2V production activities, the participatory implications of communities close to the areas where renewable energy plants are located, in other words, bottom-up manifestations, from the community to the state and multinational companies, with the involvement and participation of communities.

Final considerations

From the bibliometric mapping of publications on the Green Hydrogen Economy in the Scopus database, from its origins until August 2023, it was found that it is still little explored, the areas of Business, Management and Accounting present an important gap in research in the field of process management and, also, analysis on the subject from the perspective of sustainable development. The first scientific publication on the H2V Economy was in 2004 and has only intensified since 2019, which may have been motivated by the Paris Agreement and the environmental crisis, among other international factors.

Some countries have shown greater scientific production, such as China, Germany and the United States. The Chinese have built up a network of elaboration and co-citation of work, as evidenced by bibliometrics. South American and African research is incipient, as is the low participation of researchers from these continents in the most cited articles, which may indicate disadvantages in the competition for H2V technology.

The publications cover the production, storage, transportation and use of H2V. They outline a complex, decarbonized production chain, which is still being structured, with global reach and the potential to benefit society. The potential for decentralized energy generation and the existence of multiple sustainable sources are incentives for governments and large business groups to invest in projects and technology research, generating expectations of growth in the H2V-based economy.

The study’s main limitation is the choice of a database for mapping publications on the Green Hydrogen Economy. The Scopus database was chosen because it is internationally recognized for its rigor and excellence, because it is the broadest and has more publications than the others; however, it does not cover all the studies published on the terms 'Economy' AND 'Green Hydrogen'. To overcome this limitation, it is recommended that future research should expand the search in other databases to extend the scope of the data survey.

An agenda of future studies was proposed to advance H2V management from a sustainable development perspective. It should be noted that the H2V economy will only be consolidated when applications of this input gain scale, allowing it to be commoditized, as well as when the topic encompasses debates on management from the perspective of sustainable development. The country clusters identified are motivating factors for future research into their motivating factors and their evolution.

The consolidation of these conglomerates depends on the implementation of alliances, projects and public policies in the various countries involved. The transition from the theoretical, experimental and technological approach to research that reports on practical cases in detail, presenting real benefits and gains in scale, cost-benefit and risk analysis is the great challenge to be overcome by academia when it comes to green hydrogen.

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