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Mapping the research landscape of hydrogen supply chains: A bibliometric analysis of citations and co-citations

Marzena Frankowska *, Krzysztof Błoński **

** Institute of Management, University of Szczecin, Cukrowa 8, 71-004 Szczecin, Poland*
marzena.frankowska@usz.edu.pl
*** Institute of Management, University of Szczecin, Cukrowa 8, 71-004 Szczecin, Poland*
krzysztof.blonski@usz.edu.pl

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Abstract: The article aims to identify the most influential authors and publications in the research area of hydrogen supply chains. The analysis of the European Union's strategic documents and hydrogen strategies announced by individual countries indicate that using hydrogen in the economy is becoming significantly more important. Therefore, scientists exploring the above topics in various research settings and scopes should also expect growing interest. The hydrogen economy, including hydrogen supply chains (HSC) as a tool for its implementation, is still a relatively young and dynamic research area. This applies especially to the so-called green hydrogen supply chains where the hydrogen feedstock is the renewable energy source. This work is intended to facilitate the identification of the most essential items of already published scientific works. The work carried out a bibliometric analysis for the research area "hydrogen supply chains". As a result of the research, the following were identified: (1) the most frequently cited publications and their authors, (2) the journals and authors that had the most significant impact on research in a given area, (3) the publications to be which are most often referred to by authors writing works in the field of HSC, and (4) changes in the importance of places of publication and authors over time. Due to the complexity of the research issues, it is crucial to determine the most significant scientific achievements to date. This should constitute the basic cognitive base for properly implementing newly undertaken research: the hydrogen supply chain.

Keywords: hydrogen supply chain, bibliometric analysis, analysis of citations

Corresponding author: *Marzena Frankowska*
E-mail: marzena.frankowska@usz.edu.pl

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1. Introduction

The adverse effects of climate change are a great challenge for the global economy (Costantini & Crespi, 2013). The critical direction of policy actions in sustainable development is energy transformation, decarbonization and increasing the share of renewable energy sources (RES). Nowadays, satisfying the growing demand for energy and reducing the negative impact on the environment and society are two interrelated and most important problems of the modern world (Lu et al., 2020). These circumstances are reflected in the package of legislative proposals referred to as the European Green Deal adopted by the European Commission in July 2021. The presented assumptions aim to transform the EU into the first climate-neutral region of the world by 2050 (European Commission, 2021).

As a result, the importance of hydrogen in the global economy is growing significantly. It is directly connected with the use of renewable energy sources. RES technologies provide an excellent opportunity to mitigate greenhouse gas emissions and reduce global warming by replacing fossil fuels. Nevertheless, regardless of the indisputable advantages, RES is an unstable energy source due to the dependence of produced energy volume on non-controllable factors such as weather and time of day (Frankowska et al., 2022). The solution to these problems is the use of hydrogen. Increased interest is observed in hydrogen production technologies, methods of storing hydrogen, and the possibility of using hydrogen without emissions in various energy and industrial installations and transport. There are three essential utility functions of hydrogen (Frankowska & Rzeczycki, 2021):

- hydrogen as a fuel resulting from conversion from electricity,
- hydrogen as a form of electricity storage,
- hydrogen as a carrier of electricity (alternative form).

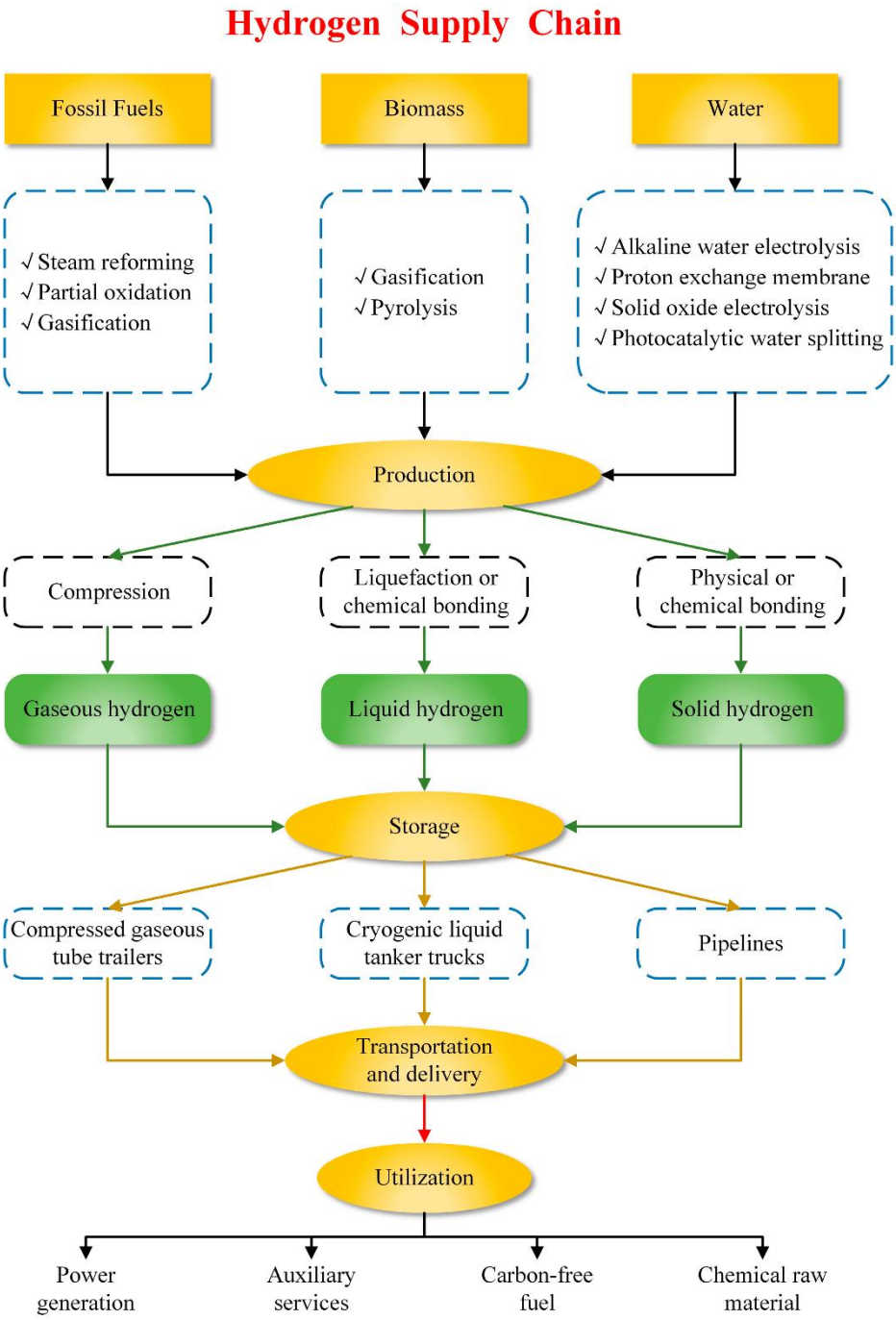
Following the war of aggression of the Russian Federation in Ukraine, hydrogen is also seen as crucial to ensuring the continent's energy security. The REPowerEU Communication takes the ambition of the European Green Deal to the next level. Its Hydrogen Accelerator sets out a strategy to double the previous EU renewable hydrogen target to 10 million tons of annual domestic production, plus an additional 10 million tons of yearly hydrogen imports by 2030. The two rounds of Important Projects of Common European Interest (IPCEI) dedicated to hydrogen, Renewable Energy Directive (RED) III, Net Zero Industry Act (NZIA), and the Hydrogen Bank will go a long way to support this. However, meeting these ambitions will require the EU to upscale its clean hydrogen economy.

In this context, hydrogen is a promising noncarbonized fuel, but the pace of its implementation will depend on the engineering advancements made at each step of its supply chain. Various hydrogen applications across industries, transport, power, and building sectors have been identified to accelerate its adoption, where it can be used as a feedstock, fuel, or energy carrier and storage. However, widespread usage of hydrogen will depend on its political, industrial, and social acceptance (Garcia-Navarro et al., 2023). Establishing a hydrogen supply chain is fundamental for achieving a hydrogen economy and the strategic goals of European energy transformation. A hydrogen supply chain (HSC) should encompass several interconnected nodes, including hydrogen production, storage, transportation, delivery, and utilization, understood as end-user consumption (Li et al., 2023). Figure 1 illustrates the key components of a hydrogen supply chain.

A critical literature analysis proves that hydrogen supply chains are a complex and demanding research area (Frankowska et al., 2022). In the theoretical achievements, separate studies have mainly focused on individual phases of the functioning of hydrogen supply chains. The first in-depth research on the hydrogen supply chain was undertaken in 2008-2012. The subject of these studies was primarily the evolution of the hydrogen market, which is strongly related to transport. They focused on distinguishing the main components in the hydrogen supply chain (Ren et al., 2012). These studies did not consider the feedstock phase, which is nowadays considered an essential component of HSC. In the first hydrogen supply chain structures, considering the supply phase, four nodes were indicated (Nunes et al., 2015): suppliers of raw materials (local or international), production plants, storage points and petrol stations. In this approach, however, the independence of research regarding individual phases of hydrogen supply chains is still visible. In the latest research (post-2015), hydrogen is more and more often considered an energy carrier and a measure stabilizing the operation of power grids, while the production of hydrogen in the electrolysis process is regarded as the optimal solution. Research focuses heavily on the strategic planning of the HSC and the deployment of hydrogen infrastructure. At the same

time, independent, in-depth research on each of the hydrogen supply chain phases is intensively developing due to the many options for their operation. Research on interconnection and interdependence in hydrogen production pathways and associated technologies is an example of the issue's complexity within one phase of the supply chain (Dawood et al., 2020).

Figure 1: Key components of a hydrogen supply chain



Sources: Li, F. et al. (2024)

The analysis of strategic documents of the European Union and hydrogen strategies announced by individual countries indicate that the topic of using hydrogen in the economy is becoming significantly more important. The hydrogen economy, including hydrogen supply chains as a tool for its implementation, is still a relatively young and dynamic research area. Therefore, we should also expect growing interest from scientists exploring the above topics in various research settings and scopes. This gives rise to the need to define a set of scientific works that will constitute a basis for embedding

research issues on hydrogen supply chains. Therefore, the article aims to identify the most influential authors and publications in the research area of hydrogen supply chains. The following research questions were formulated:

1. Which journals, authors and works are most frequently cited in the "hydrogen supply chain" research area?
2. Which journal authors have the greatest impact on research in a given area?
3. What publications are most often cited in published scientific works?
4. How does the importance of publication places and authors change over time?

The article is organized as follows: the first section introduces the importance of the hydrogen economy and supply chains. Section 2 presents the research methodology, and Section 3 reports the results. The work ends with discussing the bibliometric analysis results and the conclusions, along with the limitations of the research conducted.

2. Survey methodology

The bibliometric analysis procedure can be encapsulated in the following steps (Donthu et al., 2021): (1) Defining the objectives and scope of the bibliometric study, (2) Selecting bibliometric analysis techniques, (3) Collecting data for bibliometric analysis, (4) Conducting the bibliometric analysis and presenting the results.

The objectives of the ongoing bibliometric study are:

1. Identify which journals, authors and papers are most frequently cited in the research area "hydrogen supply chain".
2. Identify journal authors that have the greatest impact on research in a particular area.
3. Identify which publications are most often referred to in published scientific papers.
4. How has the importance of publication venues and authors changed over a given time interval (i.e., from the first identified publication on the given topic to the present day).

Citation analysis and co-citation analysis[1] were used to achieve the indicated objectives. The bibliometric data analysis was performed in two-time frames: (1) from the year of identification of the first publication on a given topic in the database to the date of performing the analysis (i.e. December 2023) and (2) divided into sub-periods allowing for tracking changes in the designated areas (division into 3 sub-periods, i.e. 2004-2013; 2014-2018;2019-2023).

A collection of publications was obtained from the Web of Science (WoS) and Scopus databases to meet the objectives. The WoS collection contained 256 documents, while the Scopus database contained 366[2] . After merging the records from both databases, a collection of 402 documents was obtained (duplicate publications occurring in both databases were removed). The completeness of the individual fields in the database was then assessed to estimate the data quality obtained. The level of missing responses is zero or low for basic document information, i.e., author(s), publication title, etc. A higher level of missingness was observed among keywords given by the authors, but this was assessed as acceptable. In contrast, the level of missingness was highest for keywords given by the machine learning algorithm within the WoS (Keywords Plus) database, meaning that any analysis using this criterion will

[1] *Citation* analysis involves measuring the number of citations a paper has received, so that an overall assessment of the quality of a paper can be made (Andreson 2006). This approach is based on the fact that citations are used to determine impact - if an article is frequently cited, it is considered important. This thesis is based on the assumption that authors cite papers that they consider important to their work (Zupic, Cater, 2015). Citations also reflect the degree of knowledge transfer and dissemination by other authors, representing other research centres (Ejdys 2016).

When two items (e.g., documents, journals or authors) are cited in the reference list of the citing item, there is a co-citation relationship between them (Osareh, 1996). Co-citation is defined as the frequency with which two entities are cited together. *Co-citation* analysis uses the number of co-citations to construct measures of similarity between documents, authors or journals. The basic premise of co-citation analysis is that the more times two items are cited together, the more likely it is that their content is related. Co-citation analysis is widely used to reveal the relationships and structure of authors, articles and journals in academic fields.

[2] The above result was obtained by adopting the following publication search criterion: *hydrogen supply chain* included in the publication title and/or keywords and/or abstract.

not reflect the accurate picture. The characteristics of the resulting set of publications are shown in Table 1.

Table 1: Basic information on the generated set of documents and the identified sub-periods

Description	Total	1st period	2nd period	3rd period
Timespan	2004-2023	2004-2013	2014-2018	2019-2023
Sources (journals, books, etc)	156	22	39	110
Documents	402	46	81	275
Average Growth Rate (%)	22,8	19,58	36,78	49,16
Average citations per doc	27,65	50,28	37,7	20,9
Document Average Age	4,66	-	-	-
References	1466	97	418	987
Keywords Plus (ID)	2190	471	443	1695
Author's Keywords	915	100	214	725
Authors	1026	100	158	832
Authors of single-authored docs	24	7	7	12
Single-authored docs	34	7	10	17
Co-Authors per Doc	3,84	3,2	3,14	4,15
article	238	31	30	177
book	5	0	4	1
review	36	2	6	28
Proceedings Paper	9	1	6	2

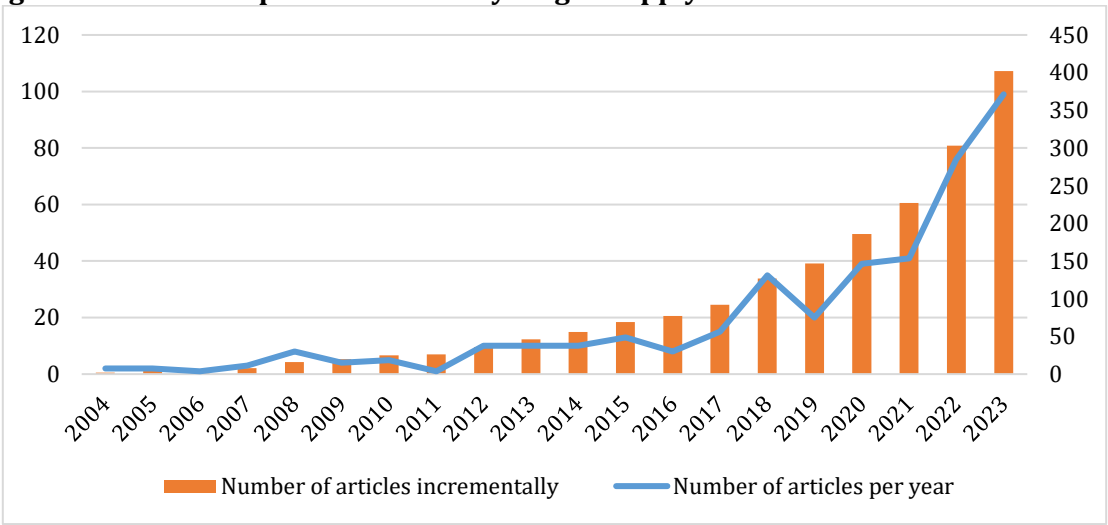
Source: Own compilation based on bibliometric analysis in Biblioshiny software

The analyses indicated using the Biblioshiny programme (Aria & Cuccurullo, 2017).

3. Results

The first publication on hydrogen supply chains was published in 2004. The above topic was not attractive to the authors who published it in the following years. Over the next six years, the number of publications exceeded only 25 pieces, while in 2018, the number reached 127. A definite increase in the number of publications can be observed since 2012. Since then, the number of publications from this area has increased by at least 8-10 pieces yearly. Figure 2 shows the evolution of the number of publications on hydrogen supply chains between 2004 and 2023.

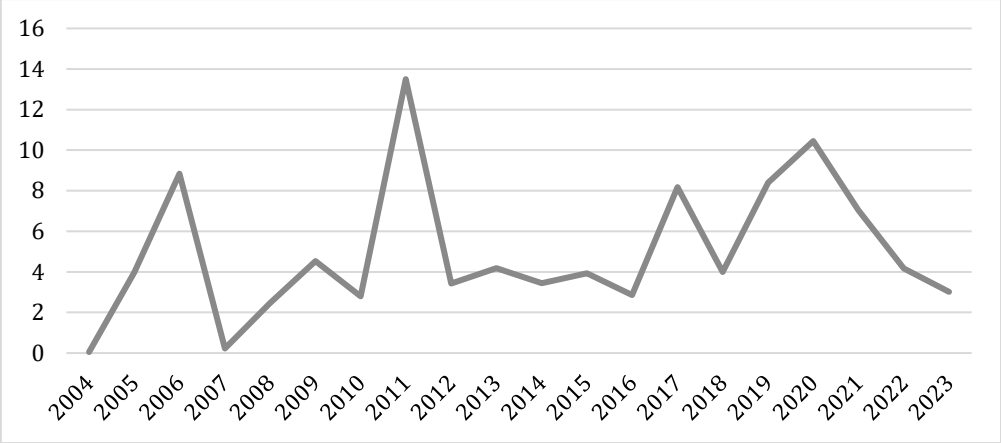
Figure 2: Number of publications on hydrogen supply chains between 2004 and 2023



Source: Own compilation based on bibliometric analysis in Biblioshiny software

A graph of average citations per year can complement the resulting picture. Analysing the data presented in Figures 2 and 3 from year to year, it is possible to see the changing interest in hydrogen supply chains.

Figure 3: Average number of citations per year by year over the period analyzed (2004-2023)



Source: Own compilation based on bibliometric analysis in Biblioshiny software

The indicated rate of increase in the number of publications had its consequences in the division of the time interval into sub-periods. The division into relatively equal sub-periods can result in significant disparities between the number of publications in the individual sub-periods. Therefore, it was decided to split the first longer sub-period (2004-2013) to obtain several publications to identify underlying values. The following two sub-periods cover the following periods - 2014-2018 and 2019-2023.

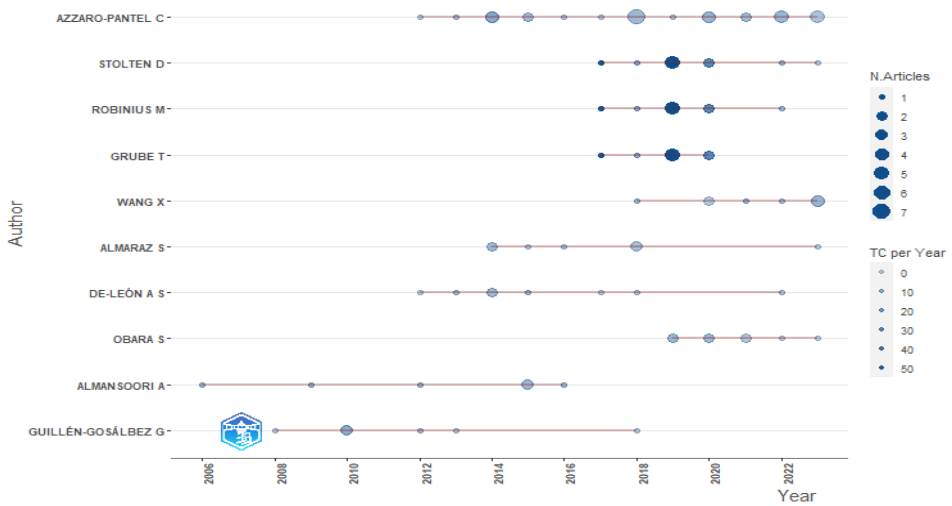
The author with the most publications on hydrogen supply chains is Azzaro-Pantel C. with 34 items (as author or co-author), followed by Stolten D., who has published 41 of them, and third place goes to Robinius M. with 10 publications. A second important element indicating the importance of a particular author to the development of a specific field of research is the number of citations of their publications in that field. Among authors publishing on hydrogen supply chains, the most frequently cited (based on citations from the WoS database) are Almansoori A. (236 citations) and Shah N. (158 citations). Another criterion by which lists of authors publishing in a given research area can be compiled can be metrics to assess the output of a given author of a publication or journal. These are the Hirsch index (h-index), Egghe index (g-index), and m-index (m-index). The authors with the most significant impact in a given research area are (WoS database): Azzaro-Pantel C. (h-index=8; g-index=14, m-index=0.62), Robinius M. (h-index=7; g-index=8, m-index=0.88), Stolten D. (h-index=7; g-index=9, m-index=0.88). A similar picture can be observed from the Scopus database. The observed differences between the set of most cited authors in the generated dataset and the generated ranking due to the value of bibliometric indices can be attempted to be explained by the fact that some of the citations may come from publications not related to the research area (i.e., coming from outside the generated set). When analyzing the positions of individual authors of a publication, it is also possible to consider the different publication periods, the publications prepared at that time and their citations (Figure 4).

In terms of publication venue, the most shared articles in this area are found in the International *Journal of Hydrogen Energy* (91 articles), Applied Energy (21 articles), and Computer-Aided Chemical Engineering (15 articles). It should be noted that the generated list of publication venues based on the number of published articles in a given area is not the only version that can be developed. Another criterion for compiling a ranking list of journals is membership in a specific set due to Bradford's law[3] . Such a list builds on, or can be considered an extension of, the earlier list by adding information on allocating a journal-title to one of three sets. The first is referred to as the 'nucleus' and contains the titles of the journals most relevant to the research field in question. The following two sets (zones) contain more journals whose general subject matter is less relevant to the topic under consideration.

[3] Bradford's Law - a principle stating that in each scientific field there is a certain fairly small set of major journals in which a significant number (about 1/3) of all the valuable publications in the field are printed. Bradford argued that if one collects journals containing articles on a topic, we can distinguish a nucleus containing the smallest number of specialised journals and further zones containing a larger number of journals whose general subject matter will be only partly or not at all related to the topic under consideration, but each zone will contain as many articles on the topic as the nucleus.

The collection, called the 'core' contains four journal titles. The three most important are the *International Journal of Hydrogen Energy, Applied Energy, and Computer-Aided Chemical Engineering*. The second collection contains 31 entries, while the third contains 121. The generated list of journal titles directly results from the number of published articles in these periodicals.

Figure 4: Summary of the most relevant authors and their publications on hydrogen supply chains during the period under review



Source: Based on bibliometric analysis in Biblioshiny software

As with determining the impact of individual authors for a given research area, a list of publication venues reflecting their relevance can be prepared, i.e., a list of journals with h-index, g-index and m-index metrics, the three most relevant journal titles are *International Journal of Hydrogen Energy* (h-index=41; g-index=64, m-index=2.05), *Applied Energy* (h-index=13; g-index=21, m-index=1.3), *Renewable and Sustainable Energy Reviews* (h-index=9; g-index=10, m-index=1.5).

A detailed list of the authors publishing most in the area and their existence, as well as a summary of the most frequent places of publication and their importance in each sub-period and overall, is provided in Table 2.

By comparing the results in Tables 1 and 2, it is possible to present some basic conclusions regarding the relevance of authors and publications throughout the analysis period. It can be seen that the number of publications on hydrogen supply chains is increasing from period to period, and the number of publications cited by the authors is also increasing. The group of authors preparing publications in this area is also increasing. This also applies to the group of authors preparing publications independently. Most publications are produced in collaboration between authors, with the average size of such teams increasing from period to period.

The International Journal of Hydrogen Energy ranks first in the number of published articles on HSC, regardless of the period analyzed. It is also the most relevant in terms of bibliometric index values. The same is true for the authors of the publications. The same author ranks first in this area and in terms of its impact (measured by the indices, i.e., h-index, g-index and m-index). This is Catherine Azzaro-Pantel.

A ranking of the most cited papers can be made based on citations from the entire database (so-called global citations) and citations based on items in the generated set of documents (so-called local citations). There may be differences between the two lists due to citations in publications from other disciplines (i.e., global citations may be more numerous than local ones).

Table 2: Summary of most relevant publication venues and authors by period

	1st period 2004-2013	2nd period 2014-2018	3rd period 2019 - 2023	Total 2004 -2023
Most Relevant Sources	International Journal of Hydrogen Energy - 23 articles; 17th World Hydrogen Energy Conference 2008; WHEC 2008 - 2 articles; Computer Aided Chemical Engineering - 2 articles.	International Journal of Hydrogen Energy - 18 articles; Hydrogen Supply Chain: Design, Deployment and Operation - 10 articles; Computer Aided Chemical Engineering - 5 articles.	International Journal of Hydrogen Energy - 50 articles; Applied Energy -17 articles; Proceedings of WHEC 2022 - 23rd World Hydrogen Energy Conference - 11 articles.	International Journal of Hydrogen Energy - 91 articles; Applied Energy - 21 articles; Computer Aided Chemical Engineering - 15 articles.
Cited Sources (most cited sources in the generated dataset)	International Journal of Hydrogen Energy - 24 citations; Energy Policy - 9 citations; Expert Syst Appl - 9 citations	International Journal of Hydrogen Energy - 106 citations; Applied Energy - 28citations; Renewable and Sustainable Energy Reviews - 20 citations.	International Journal of Hydrogen Energy - 152 citations; Applied Energy -60 citations; IEEE T IND APPL -30 citations; Renewable and Sustainable Energy Reviews -30 citations.	International Journal of Hydrogen Energy - 282 citations; Applied Energy -91 citations; Renewable and Sustainable Energy Reviews - 53 citations.
Sources' Impact by H-index, G-index and M-index.	International Journal of Hydrogen Energy - h-index=21; g-index=23, m-index=1.05; Computer Aided Chemical Engineering - h-index=2; g-index=2, m-index=0.13; 17th World Hydrogen Energy Conference 2008, WHEC 2008 - h-index=1; g-index=1, m-index=0.059.	International Journal of Hydrogen Energy - h-index=12; g-index=18, m-index=1,09; Hydrogen Supply Chain: Design, Deployment And Operation - h-index=5; g-index=8, m-index=0,71; Applied Energy - h-index=4; g-index=4, m-index=0,4	International Journal of Hydrogen Energy - h-index=22; g-index=39, m-index=3.67; Applied Energy - h-index=11; g-index=17, m-index=1.83; Renewable and Sustainable Energy Reviews -h-index=9; g-index=10, m-index=1.5	International Journal of Hydrogen Energy - h-index=41; g-index=64, m-index=2.05; Applied Energy - h-index=13; g-index=21, m-index=1.3; Renewable and Sustainable Energy Reviews - h-index=9; g-index=10, m-index=1.5;
Most Relevant Authors	Guillén-Gosálbez G. - articles =6; articles fractionalized =1.75; Almansoori A. -articles =3; articles fractionalized =1.5; Han J. -articles =3; articles fractionalized =1.0.	Azzaro-Pantel C. articles=15; articles fractionalized =6,65; Almaraz S. articles=7; articles fractionalized =2,11; De-León A. S. articles=5; articles fractionalized =1,53.	Azzaro-Pantel C. - articles =17, articles fractionalized =4.84; Stolten D. - articles =9, articles fractionalized =1.64; Obara S. - articles =8, articles fractionalized =4	Azzaro-Pantel C. - articles =34; articles fractionalized =11.89; Stolten D. - articles =11; articles fractionalized =1.95; Robinius M. - articles =10; articles fractionalized =1,70

Source: Own compilation based on bibliometric analysis in Biblioshiny software

In both databases (i.e. WoS and Scopus), the most cited publications from this area are: Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipinski, W., & Khalilpour, K. R. (2020), *Hydrogen as an energy vector* (TC_W =490; TC_S = 547); Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., & Stolten, D. (2017). *Seasonal storage and alternative carriers: A flexible hydrogen supply chain model* (TC_W =367; TC_S = 424) and Noussan, M., Raimondi, P. P., Scita, R., & Hafner, M. (2020). *The role of green and blue hydrogen in the energy transition - A technological and geopolitical perspective* (TC_W =266; TC_S = 297).

The second type of citation, i.e., local citations, usually duplicates the article examples indicated for global citations. The difference usually concerns the ranking position of the article in question. However, they are completely different positions in this case, although they are identical publications in both databases. In first place is an article by Almansoori, A., & Shah, N. from 2006, entitled: *Design and Operation of a Future Hydrogen Supply Chain: Snapshot Model*. This article has been cited 57 times in the WoS database and 65 times in the Scopus database. This is followed by the article by Almansoori, A., & Shah, N. (2009). *Design and operation of a future hydrogen supply chain: multi-period model* (cited in WoS 53 times and in Scopus 71 times). The third publication is Kim, J., Lee, Y., & Moon, I. (2008). *Optimization*

of a hydrogen supply chain under demand uncertainty (cited in WoS 48 times, while in Scopus 60 times). The indicated examples of publications can be seen as the most relevant part of the 'must-read' list. These are items with which a potential author researcher should necessarily become familiar.

In a situation where we limit the time frame only to, for example, the last five years, it is possible to extract publications that constitute the so-called knowledge base (intellectual base)[4]. The collection of the first five most cited items in each database for 2019-2023 is presented in Table 3.

Table 3: A collection of the top five most cited items in the WoS and Scopus databases from 2019 to 2023

Lp.	Most cited publications in the database	Most cited publications in the generated set
	WoS	
1	Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipinski, W., & Khalilpour, K. R. (2020). Hydrogen as an energy vector.	Reuß, M., Grube, T., Robinius, M., & Stolten, D. (2019). A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany.
2	Noussan, M., Raimondi, P. P., Scita, R., & Hafner, M. (2020). The role of green and blue hydrogen in the energy transition-A technological and geopolitical perspective.	Li, L., Manier, H., & Manier, M. A. (2019). Hydrogen supply chain network design: An optimization-oriented review.
3	Abad, A. V., & Dodds, P. E. (2020). Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges.	Talebian, H., Herrera, O. E., & Mérida, W. (2019). Spatial and temporal optimization of hydrogen fuel supply chain for light duty passenger vehicles in British Columbia.
4	Ratnakar, R. R., Gupta, N., Zhang, K., van Doorne, C., Fesmire, J., Dindoruk, B., & Balakotaiah, V. (2021). Hydrogen supply chain and challenges in large-scale LH2 storage and transportation.	Seo, S. K., Yun, D. Y., & Lee, C. J. (2020). Design and optimization of a hydrogen supply chain using a centralized storage model.
5	Reuß, M., Grube, T., Robinius, M., & Stolten, D. (2019). A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany.	Tlili, O., Mansilla, C., Linβen, J., Reuss, M., Grube, T., Robinius, M., ... & Stolten, D. (2020). Geospatial modelling of the hydrogen infrastructure in France in order to identify the most suited supply chains.
	Scopus	
1	Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipinski, W., & Khalilpour, K. R. (2020). Hydrogen as an energy vector	Li, L., Manier, H., & Manier, M. A. (2019). Hydrogen supply chain network design: An optimization-oriented review.
2	Noussan, M., Raimondi, P. P., Scita, R., & Hafner, M. (2020). The role of green and blue hydrogen in the energy transition-A technological and geopolitical perspective.	Talebian, H., Herrera, O. E., & Mérida, W. (2019). Spatial and temporal optimization of hydrogen fuel supply chain for light duty passenger vehicles in British Columbia.
3	Abad, A. V., & Dodds, P. E. (2020). Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges.	Tlili, O., Mansilla, C., Linβen, J., Reuss, M., Grube, T., Robinius, M., ... & Stolten, D. (2020). Geospatial modelling of the hydrogen infrastructure in France in order to identify the most suited supply chains.
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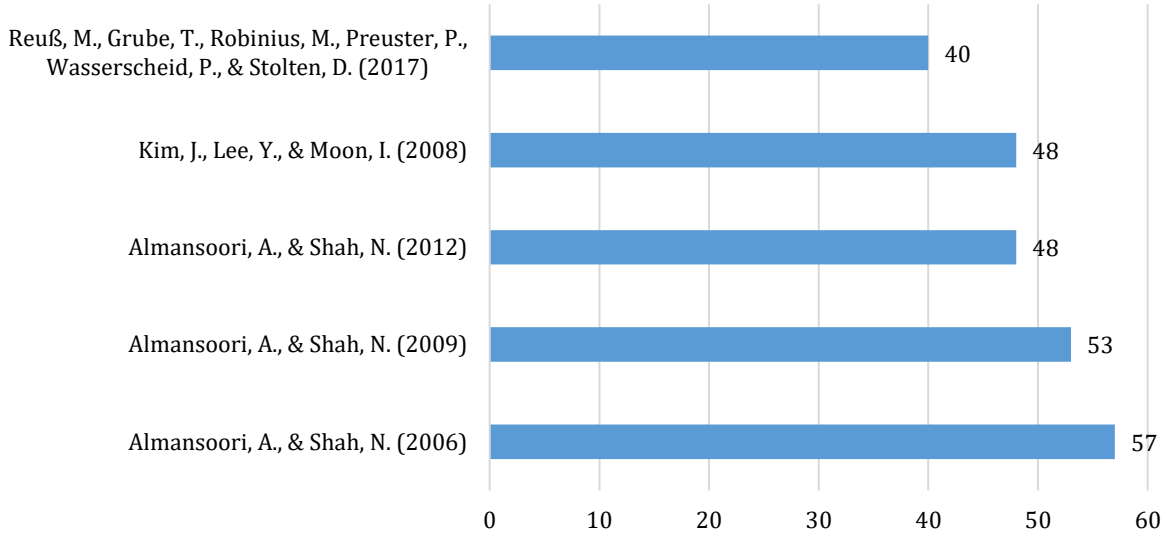
5	Reuß, M., Grube, T., Robinius, M., & Stolten, D. (2019). A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany.	Cerniauskas, S., Junco, A. J. C., Grube, T., Robinius, M., & Stolten, D. (2020). Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study.

Source: Own compilation based on bibliometric analysis in Biblioshiny software

[4] The knowledge base of a field is the collection of articles most frequently cited by current research. This is sometimes also referred to as the 'intellectual base' (Persson, 1994).

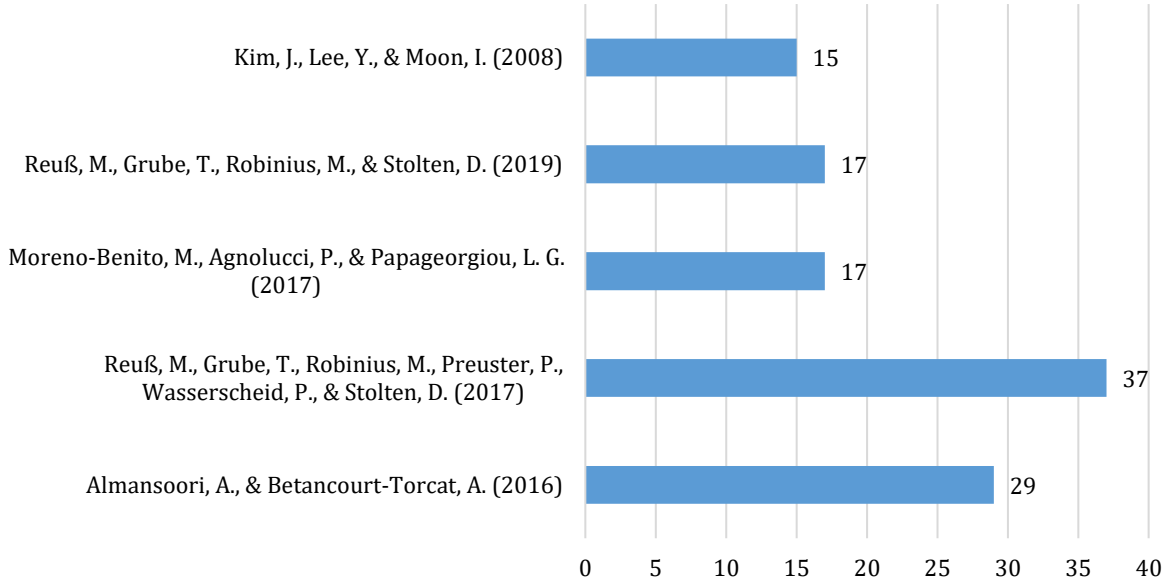
Co-citation analysis makes it possible to determine the frequency with which two entities are cited together, i.e., a co-citation relationship is established between them. In the case of the collection of publications analyzed, the five most frequently cited items of literature in the bibliographic lists in the publication databases are each presented in Figures 5 and 6.

Figure 5: The five most frequently cited literature items in bibliometric lists in the WoS database



Source: Own compilation based on bibliometric analysis in Biblioshiny software

Figure 6: The five most frequently cited literature items in bibliometric lists in the Scopus database



Source: Own compilation based on bibliometric analysis in Biblioshiny software

Such a compilation allows the identification of publications (selected using citation thresholds) that are considered necessary by their citing researcher (Zupic, Cater, 2015). In this case, seven publications considered most important by the citing authors of publications in hydrogen supply chains can be identified.

4. Discussion and conclusions

The objectives indicated in the research methodology section resulted in using only data on publications and their authors in the citation and co-citation analysis. For the citation analysis, some of the measures related to the use of authors' affiliations of papers and information related to their country of origin were omitted. On the other hand, the co-citation analysis omitted, for example, the places of publication of individual papers. This does not change that the information collected (Table 4) allowed answers to the objectives set.

Table 4: Summary of results obtained in the analysis of citations and co-citations of the term "hydrogen supply chains"

Basic data	Citation analysis	Co-citation analysis
• First publication on HSC: 2004. • Identified collection of publications on HSC: 256 items in WoS, 366 items in Scopus, after merging both collections 402 items (documents). • Average number of authors per paper: 3,84. • The highest number of new publications on HSC was recorded in 2023, i.e. 99 publications • Average age of document (in years): 4,66.	• Average number of citations per document: 27,65 • The author who has published the most papers on HSC: C. Azzaro-Pantel (34 items). • Author with greatest influence on other publications: C. Azzaro-Pantel. • The place with the most papers on HSC was the International Journal of Hydrogen Energy (91 papers). • The most relevant publication venue: International Journal of Hydrogen Energy. • The highest average number of citations per year: 13,5 (2011 r). • Global citation. The most cited papers in both databases are Abdin et al (2020). • Local citations. Most cited paper in both databases: Almansoori, Shah, (2006) - 57 citations (WoS) and 65 citations (Scopus). • Intellectual base (top 3 positions): Abdin et al (2020), Noussan (2020), Abad et al. (2020)	• Most co-cited publications (first three items): Almansoori, A., & Shah, N. (2006); Almansoori, A., & Shah, N. (2009); Almansoori, A., & Shah, N. (2012).

Source: Own compilation based on bibliometric analysis in Biblioshiny programmes

The first stated objective concerned the most frequently cited publications and their authors in the field of HSC. The most cited publication is the work of Abdin et al. (2020). This is followed by the work of Reuß et al. (2017) and Noussan (2020). When restricting citations only to the generated set of publications, the ranking is as follows: Almansoori, Shah (2006), Almansoori, Shah (2009) and Kim et al. (2008). It should be noted that the last three publications indicated were published relatively long ago. The rule of thumb that the longer the citation years, the greater the chance of getting more citations compared to more recently published articles works well here. This does not change the fact that the publications identified in both lists form a list of journals that should be consulted when studying the issue of hydrogen supply chains. The second aim was to identify the journals and authors that have had the most significant impact on research in the field. Three such journals include International Journal of Hydrogen Energy, Applied Energy, Renewable and Sustainable Energy Reviews. Among the authors with the most significant research impact are Azzaro-Pantel C., Robinius M., and Stolten D. The third objective identified was identifying the publications most frequently referred to by authors writing HSC papers. These are Almansoori, A., & Shah, N. (2006); Almansoori, A., & Shah, N. (2009); Almansoori, A., & Shah, N. (2012). The last objective was to show changes in the importance of publication venues and authors over time. In this case, it can be said that the division into sub-periods did not indicate significant changes, only a strengthening of the position of individual journal titles and the authors of publications in the field. This study demonstrates that cogitation analysis and bibliographic coupling can produce valid representations of the research field, which is essential for exploring the relatively new research area of HSC.

The obtained research results are worth comparing with the results of bibliometric analyzes conducted by other authors, and the importance of hydrogen supply chains can be concluded directly or indirectly. In the first case, two publications by Kumar Kar et al. (2022) and Raman et al. (2022) are

worth referring to. In "*Bibliometric analysis of the research on hydrogen economy: An analysis of current findings and roadmap ahead*", Sanjay Kumar Kar and his co-authors note that hydrogen supply chains and hydrogen fuel cells are the main identified topics. The results of their analyses show that research on the hydrogen economy mainly concerns multidisciplinary aspects, by which they mean, however, separate research in the field of production, storage, transport, the use of hydrogen and the formulation of public policy. The opposite role of hydrogen supply chains can be seen in the second work, Raman, R. et al. (2022), titled "*Green-hydrogen research: What have we achieved, and where are we going? "Bibliometrics analysis*." Based on the results of the keyword co-occurrence analysis, it was found that hydrogen supply chains are part of the largest cluster containing the most publications and the most frequently cited, but their position in the generated network graph indicates marginal importance in this area. This position is closer to our research results because it treats the hydrogen value chain as an integrated research entity.

As already mentioned, the role of hydrogen supply chains in publications can also be indirectly inferred. In this case, you should define a category (term) that illustrates the scope of interest in the selected aspect of the researched area. In this work, the concept of hydrogen infrastructure was chosen as it is an essential element of the flow of physical streams conditioning the functioning of the entire hydrogen supply chain. The hydrogen infrastructure includes, among others: installations for production, storage, compression, transport, distribution of hydrogen, refueling stations, and the transmission network. Therefore, it can be assumed that hydrogen supply chains are part of a broader set: hydrogen infrastructure. In this case, it is worth referring to the publication by Yap and McLellan (2023) on the historical analysis of research directions in the hydrogen economy in the years 1997-2020. The authors divided the indicated period into three sub-periods, and within two intervals, i.e. 2000-2009 and 2010-2020, one can notice the changing importance of issues related to hydrogen infrastructure and its increasing importance. Hydrogen supply chains are the primary tool for implementing the hydrogen economy, the aim of which is an energy transformation that will enable achieving the objectives of decarbonization, climate neutrality and energy security. The current fragmentation of hydrogen supply chains makes it impossible to achieve economies of scale using hydrogen technologies. This applies especially to the so-called green hydrogen supply chains obtained from RES. The connections between the processes of supply, production, and distribution of hydrogen as an emission-free carrier of electricity are disrupted and fragmented. Technological progress must be accompanied by scientific development. A growing interest among researchers in the issue of hydrogen supply chains should be expected. Therefore, it is crucial to determine the most significant scientific achievements to date. It should constitute the essential cognitive base for properly implementing newly undertaken research. This work is intended to facilitate the identification of the most essential items of already published scientific works.

Further research is planned in the future, this time to identify so-called research fronts. In other words, these new research directions scientists undertake allow us to determine the most exciting vectors for developing a given research area. This will be particularly interesting concerning hydrogen supply chains, a young and dynamically developing field of research.

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Conflicts of interest

The authors declare no conflict of interest.

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