Global Trends in PEM Electrolyzer Research Based on Published Articles

Ziwei Bai[1](✉), Jiahua Li[1], Zhanfeng Deng[1], Hui Tan[1], Lu Li[1], Guizhi Xu[1], Wei Kang[1], and Min Liu[2]

[1] State Grid Smart Grid Research Institute, Beijing 102206, China
baiziwei0427@sina.com

[2] Research Institute of State Grid Zhejiang Electric Power Co., Ltd., Hangzhou, Zhejiang, China

Abstract. As one of the representative new energy, hydrogen has received widely attention in recent years. PEM electrolyzer plays a central role in hydrogen production process. In this paper, 411 publications related to PEM electrolyzer collected from Web of Science released between 2005 and 2022 were analyzed through bibliometric to explore research hot-spots and future trends by analyzing publication and citation, countries and authors, journals and keywords. According to statistics and analysis, (1) Iran and Dincer Ibrahim were the most productive countries and authors, respectively. (2) International Journal of Hydrogen Energy was the mainly journal of PEM electrolyzer related publications. (3) Component and Hybrid System are likely to remain prominent areas of research in the foreseeable future. (4) Current hot-spots, such as Two Phase Flow and Hybrid System, may receive even more attention in the foreseeable future.

Keywords: PEM electrolyzer · Bibliometric · Hydrogen energy · Trend expectation

1 Introduction

Hydrogen has become one of the most promising clean and sustainable energy [1] due to its non-carbon emissions, which could make great contributions to the construction of global carbon neutral energy system. Hydrogen can be produced from various resources including fossil fuels [2–4], biomass [5], biological sources [6], and water electrolysis [7]. In contrast, electrolysis is the most economical method for large-scale production of high-purity ($> 99.99\%$) hydrogen, which could be further classified into alkaline water electrolysis (AWE), solid oxide electrolysis (SOE), and proton exchange membrane (PEM) water electrolysis.

SOE is easy to achieve high producing efficiency [8], but the technology is still trapped in the laboratory stage and lacks of industrial application. AWE has become a well matured technology for hydrogen production up to the megawatt range, and constitutes the most extended electrolytic technology at a commercial level worldwide [9]. But its disadvantages including low partial load range and limited current density [10] limit the promotion of this technology and the enthusiasm of relevant academic research.

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PEM by contrast, as a novel electrolysis method, has the advantages of high flexibility, compact equipment and high current density [11]. With the trial of non-noble metal catalysts utilization [12], more and more important achievements were accomplished in recent years, and in summary, the disadvantages of PEM are gradually overcome and the number of published papers related to PEM electrolysis is rapidly increasing (as summarized in Sect. 3.1).

Over the past two decades, more than 400 articles are published on the R&D of PEM electrolyzer, and the development road map of PEM electrolyzer over the years has been gradually clear. Thus, the purpose of this paper is to analyze the modification of research hot-spots in the field of PEM electrolyzer based on the publications, in order to offer beneficial inspirations and new frontiers for relevant scholars.

2 Methods

2.1 Data Collection

Relevant articles are identified from the Web of Science Core Collection (WoSCC) database. To avoid issues due to daily updates of the database, we conducted our search and downloaded relevant items on January 3, 2023, Tuesday (Fig. 1). We used search formulae as TS = ("PEM Electrolyzer"). The search terms were selected from the Science Citation Index Expanded (SCI-EXPANDED). A total of 444 publications were retrieved. After excluding 33 publications including early access, proceeding paper, corrections, meeting abstract, 411 articles were included in the final data set. Full records and cited refernces were exported as plaint text files for further analyses.

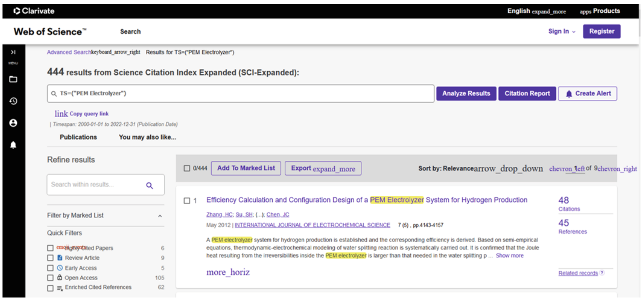


Fig. 1. Screenshot of web of science searching

The obtained data were imported into Citespace software (version 6.1.6) for deduplication. The number of publications, citations, countries, authors, journals, highly cited references, keywords, and other data were extracted by several independent researchers (JH Li, ZF Deng, H Tan, L Li) for data recheck. The H-index and average citations per items (ACI) utilized in the paper are calculated by ZW Bai based on information at WoS Online.

2.2 Data Analyses

Data collected from WoSCC needed to be further analyzed to accurately acquire the impact of each part. Citespace (version 6.1.6) and VOSviewer were introduced to bibliometric analysis and visual display. Microsoft Excel (version 16.58) was used to summarize relevant information in tables. Flow chart of publication filtering and analysis was shown in Fig. 2.

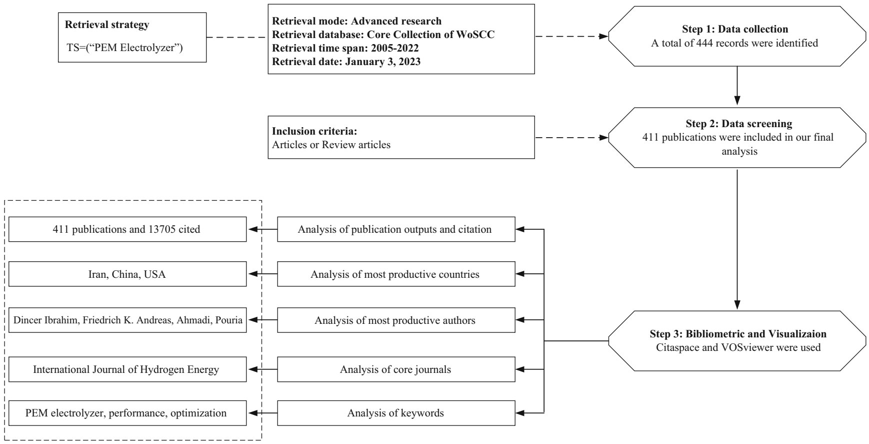


Fig. 2. Flow chart of publication filtering and analysis

3 Results

The above mentioned 411 samples published in 99 Journals were completed by 1382 authors from 60 countries/regions and affiliated to 506 organizations. These contents would be further described and analyzed through Publication and Citation, Regions and Countries, Authors, Journals, and Keywords, respectively. Details are shown as following.

3.1 Publication and Citation

As can be seen from Fig. 3, the total publications was relatively flat before 2017, and then the numbers displayed a sharply increasing trend since 2018. Almost 73.6% of total were published between 2018 and 2022. Citations almost rose straightly after 2018 too. It can be seen that the PEM Electrolytic is a research hot-spots indeed. Relevant research increases year by year.

The top 10 most-cited articles were listed in Table 1 in order to outcome the most influential paper in this field. The most-cited paper [13] is written by Barbir, F with 708 times cited, followed by papers [14–16] which has been cited for 307 times, 294 times, and 286 times, up to now, respectively.

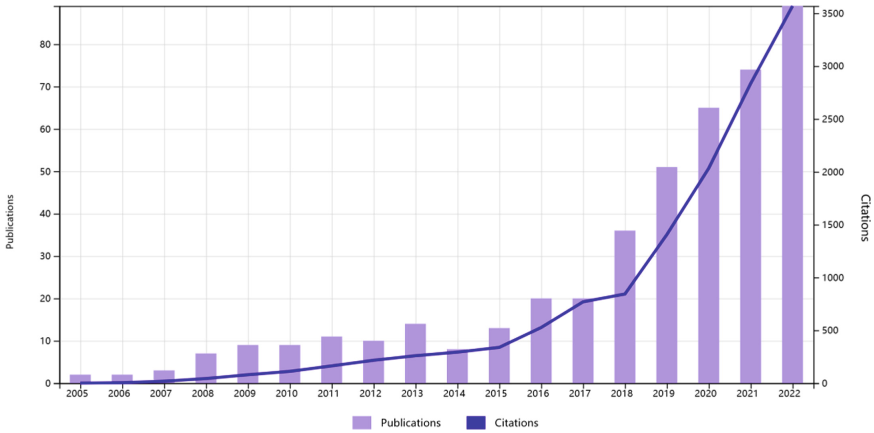


Fig. 3. Trends of publications and citations

The first mentioned one [13] is the first published paper related to PEM electrolyzer which discussed several possible applications for PEM electrolyzer including grid connected hydrogen generation, grid peak shaving, and power storage cooperated with fuel cell. Furthermore, several specific issues including size, operation, and efficiency are discussed in the paper. The second article [14] in the table should be paid specially attention. Because it published recently and been cited for 43.9 times annually. This paper is mainly study about the active and highly stable catalysts and several experiments and analysis were cleverly made. The fourth publication [16] in Table 1 is the most-cited article in 2022 which is mainly focus on the Energy and exergy analysis of a PEM electrolyzer system, and offered better understanding of the characteristics of PEM electrolyzer plant. This paper represents the boom of PEM electrolyzer system related research.

3.2 Publication and Citation

Figure 4 displays the distribution of total publications about PEM electrolyzer. Iran (88), China (61), USA (59), Germany (52), Canada (50), Turkey (50), Italy (32), France (27), South Korea (14), Japan (12) as the top 10 most productive countries up till 2022. These countries are mainly located in Asia, Europe and North America. Data in Fig. 4 is not directly equal to value in Fig. 3, because some articles are finished through global cooperation and will be duplicated statistics.

3.3 Authors

Tabel 2 summaries the top 10 authors in terms of the number of publications. Dincer, Ibrahim from University of Ontario was the most productive author with 22 publishments up to 2022. His outstanding investigation has significantly increased the number of related papers published from Canada, accounting for about 44%. In the same way, Iran, as the most productive country mentioned in Sect. 3.2, also owes its outstanding scientific

Table 1. High cited references in PEM electrolyzer

Rank	Title	Author	PY	Citation						
				2018	2019	2020	2021	2022	APY	Total
1	PEM electrolysis for production of hydrogen from renewable energy sources	Barbir, F.	2005	52	66	61	64	53	39.33	708
2	Oxide-Supported IrNiOx Core-shell particles as efficient, Cost-effective, and stable catalysts for electrochemical water splitting	Nong, H. N.; Oh, H. S.; Reier, T.	2015	38	51	56	47	32	38.38	307
3	Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage	Ipsakis, D.; Voutetakis, S.; Seferlis, P.	2009	21	19	22	22	12	21	294
4	Energy and exergy analysis of hydrogen production by a proton exchange membrane (PEM) electrolyzer plant	Ni, M.; Leung, M. K. H.; Leung, D. Y. C.	2008	22	36	41	45	63	19.07	286
5	Oxide-supported Ir nanodendrites with high activity and durability for the oxygen evolution reaction in acid PEM water electrolyzers	Oh, H. S.; Nong, H. N.; Reier, T.	2015	24	47	44	55	35	31.25	250

(*continued*)

Table 1. (*continued*)

Rank	Title	Author	PY	Citation						
				2018	2019	2020	2021	2022	APY	Total
6	Dynamic modelling of a proton exchange membrane (PEM) electrolyzer	Gorgun, H.	2006	10	13	13	18	22	11.06	188
7	Optimization of solar powered hydrogen production using photovoltaic electrolysis devices	Gibson, T. L.; Kelly, N. A.	2008	6	12	7	20	6	11.6	174
8	Energy and exergy analyses of hydrogen production via solar-boosted ocean thermal energy conversion and PEM electrolysis	Ahmadi, P.; Dincer, I.; Rosen, M. A.	2013	16	25	25	22	33	17.1	171
9	Ultrathin IrO_2 Nanoneedles for electrochemical water oxidation	Lim, J.; Park, D.; Jeon, S. S.	2018	5	28	38	45	41	31.6	158
10	Nanosized IrOx-Ir catalyst with relevant activity for anodes of proton exchange membrane electrolysis produced by a cost-effective procedure	Lettenmeier, P.; Wang, L.; Golla-Schindler, U.	2016	27	22	29	29	21	20.57	144

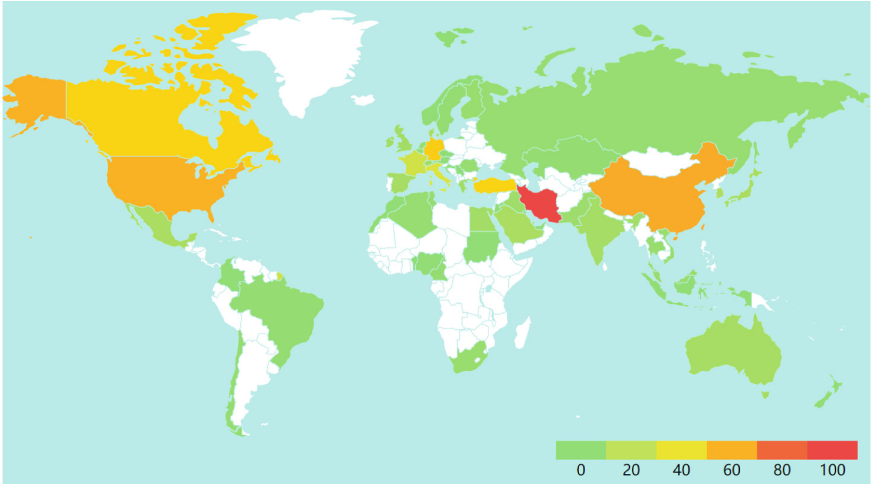


Fig. 4. Geo visualization of research distribution of PEM electrolyzer. *Note* Color relates to the paper released (*Note* Taiwan belongs to China; England, Northern Ireland, Scotland and Wales belongs to UK.)

research contributions to research teams led by Afshari, Ebrahim and Baniasadi, Ehsan. As can be seen, the rise of an outstanding scholar (team) has a significant impact on the research status of the country in relevant fields. While it is also important to find that as the second largest publication country, China, do not have any outstanding researcher being recorded in Table 2. It is considered as up to now, this topic has been greatly attracted by Chinese researchers but no one has become the academic leader.

3.4 Journals

There were 99 journals used to publish PEM electrolyzer related papers, in which the International Journal of Hydrogen Energy contributed the most articles with total publications of 147 (33.1%), and Energy Conversion and Management ranked second (36, 8.1%), followed by Journal of Power Sources (23, 5.2%) (Fig. 5).

3.5 Keywords

VOS viewer which could be used to classified the similar keywords was introduced, 411 publications contained 1891 keywords, and 180 left after merging of similar items. Heat map of Keywords (Fig. 6) highlights the top keywords including PEM Electrolyzer, Performance, Energy, Hydrogen Production, and Optimization. These keywords related to the deep research around PEM electrolyzer especially on catalyst and system performance.

Table 2. Most productive authors in PEM Electrolyzer.

Rank	Author	Country	Counts	Institutions	H-Index	ACI*
1	Dincer, Ibrahim	Canada	22	University of Ontario	104	34.43
2	Friedrich, K. Andreas	Germany	14	University of Stuttgart	48	35.09
3	Ahmadi, Pouria	USA	12	University of Illinois at Urbana-Champaign	47	54.68
4	Bazylak, Aimy	Canada	11	University of Toronto	34	20.17
5	Afshari, Ebrahim	Iran	11	University of Isfahan	25	27.98
6	Ozturk, Murat	Holland	11	Isparta University of Applied Sciences	20	19.40
7	Gago, A. Saul	Germany	10	Helmholtz Association	23	33.72
8	Baniasadi, Ehsan	Iran	10	University of Isfahan	21	23.52
9	Guilbert, Damien	France	9	Universite de Lorraine	13	12.11
10	Alirahmi, S. Mojtaba	Denmark	9	Aalborg University	10	33.07

[*]ACI average cited index

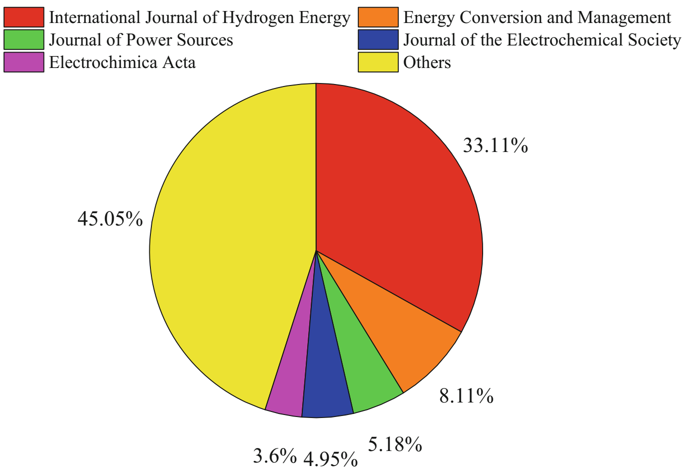


Fig. 5. Pie chart visualization of the top journals of PEM electrolyzer

4 Discussion

4.1 Countries and Authors

Figure 7 demonstrates the annual publications of top 10 most productive countries since 2014. Iran, China and USA are the top 3 countries who contributed the most publications as previous shown in Fig. 4. Iran has far more publications than any other country (20%), most of which are finished in recent 5 years [17–21]. Iran remains the most producer in recent five years, until been surpassed by China (23) in 2022.

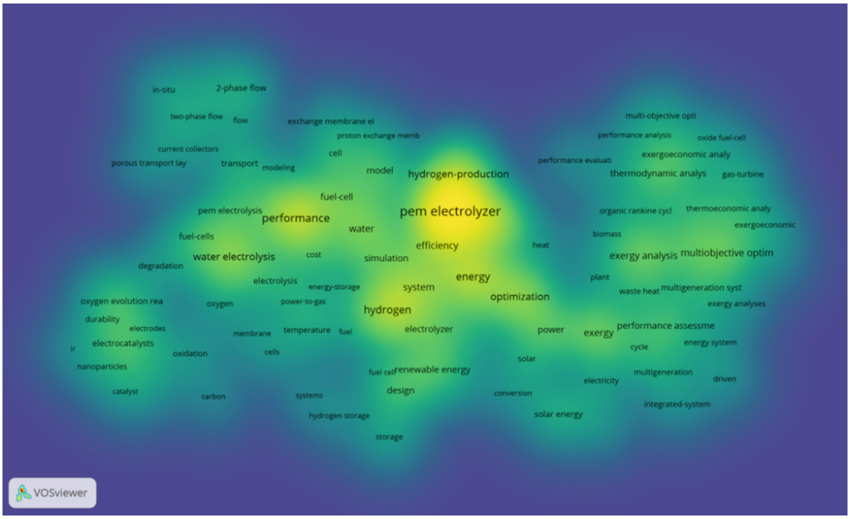


Fig. 6. Heat map of keywords in 2022

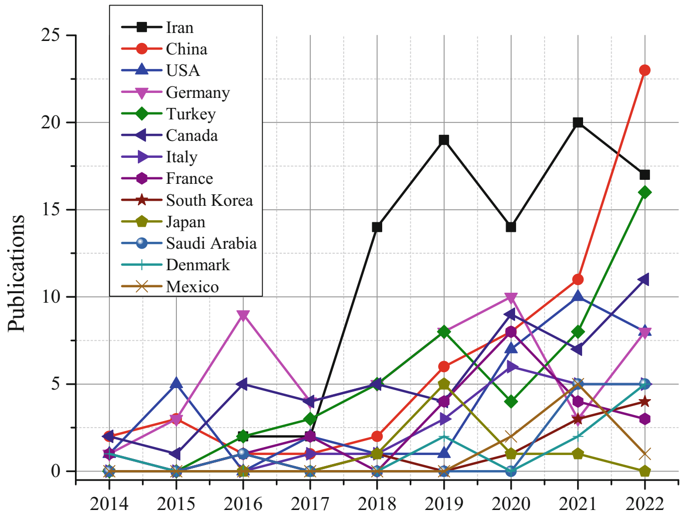


Fig. 7. Trends of publications of the top 10 countries/regions

Author cooperation analysis revealed inter-author connection networks. In the PEM Electrolyzer research area, Dincer Ibrahim (22), Friedrich K Andreas (14), Ahmadi, Pouria (12) are the top 3 authors with the most paper publications. And it can be seen from Fig. 8, which summarised the authors with more than 4 papers published, as some of these authors have quiet close stable team cooperation. Dincer, Ibrahim and Ahmadi, pouria used to co-work on the energy analysis and optimization of electrolyzer included system since 2013 [22–25]. Friedrich, Wang, Abouatallah, and bazylak are together engaged in the characteristics investigation of gas diffusion layer and bipolar of PEM electrolyzer [26–31].

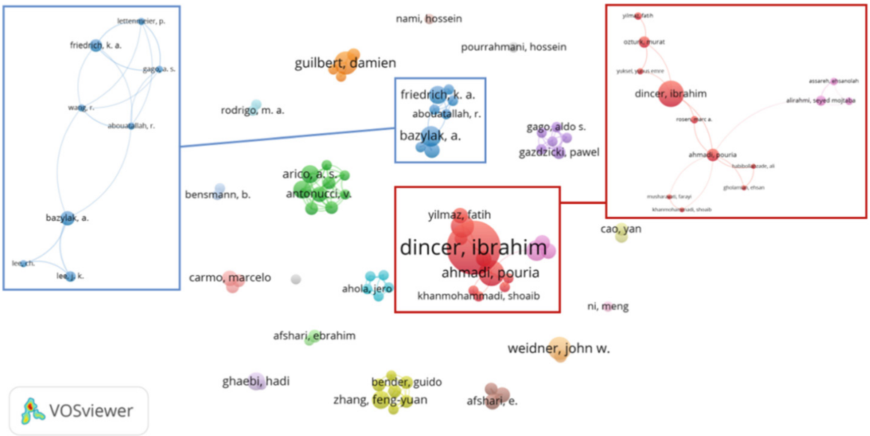


Fig. 8. Network visualization map of co-authorship. *Notes* the size of the nodes reflects the strength of their cooperation.

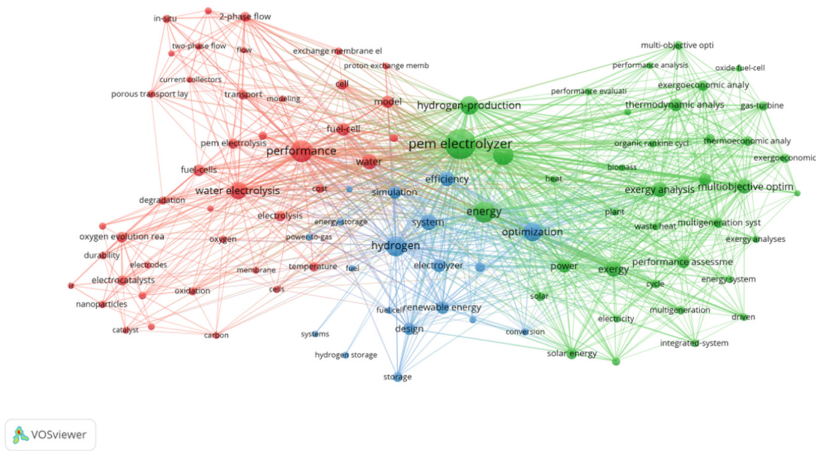
4.2 The Changing of Keywords

The keywords clarification through these papers are summarized as Fig. 9. It could be seen as three cluster are summarized with different colors, System type (Exergy Analysis, Multi-objective Optimization, et al.), component type (Two Phase Flow, Oxygen Evolution Reaction, et al.), and modeling type (Simulation, Design, et al.), which may related to system, component, and electrolyzer, respectively. Furthermore, the annual keywords in Fig. 10b clearly shows that the keywords on the right are newer, which emphasize that the research focus shifted from system into component gradually. This phenomenon is predictable, as technical research should gradually modification from application demonstration to theoretical verification.

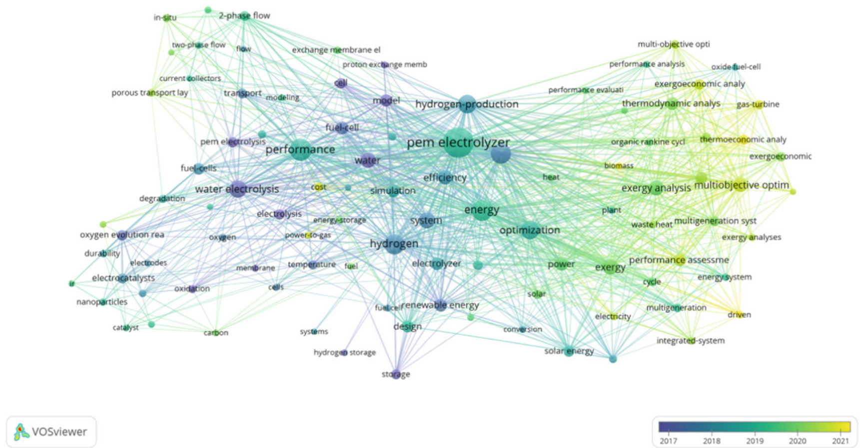
Moreover, the verification of the keywords are summarized as Fig. 10. It is partial similar with the result presented in Fig. 9. Not only the component study related keywords, such as Modelling and Degradation [32–35] shows increment these years, but also the Hybrid System related keywords, such as Geothermal and Photovoltaic [21, 36–38], show a boom increment these years. As for the System Optimum Analysis and Oxygen Evolution Reaction, these keywords fail to present a continuous research trend and seem suspended.

4.3 Recent Research Trends

To analyze the subtle changes in research over recent years, the heat map of keywords till 2020 is drawn(as shown in Fig. 11) to compare with Fig. 6. The hot keywords related



(A)Network visualization map of keywords



(B)Overlay visualization of keywords co-occurrence year

Fig. 9. Analysis of keywords for PEM electrolyzer (*Notes* the size of the nodes reflects the strength of their frequency)

to Performance and Optimization are slightly decreased during 2020–2022, which are replaced by publications about Modelling and Two Phase Flow. This trend modification is consistent with the research topic timeline as shown in Fig. 10.

Moreover, several outstanding authors are chosen for case analysis for the trend modification on researching area in PEM electrolyzer. The most prolific authors in the area are summarized in Table 3 as basic data, and their latest publications during 2020–2022 are utilized for special analysis.

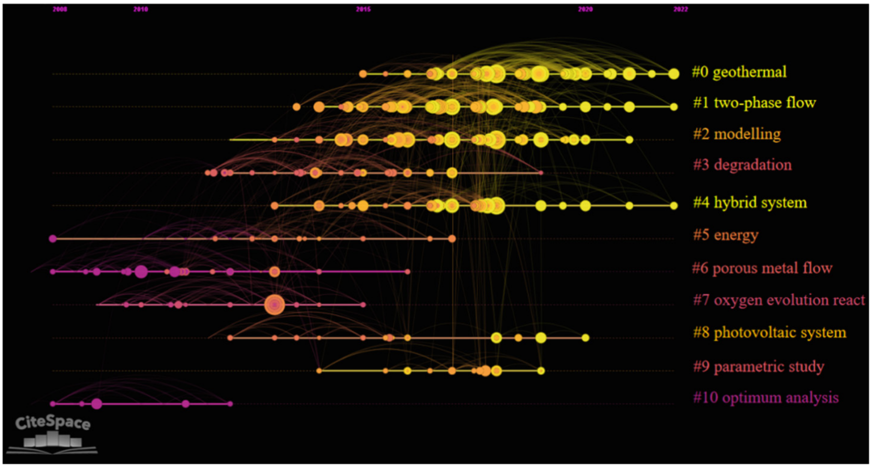


Fig. 10. Cluster timeline of co-cited reference (*Notes* the size of the nodes reflects the strength of their frequency)

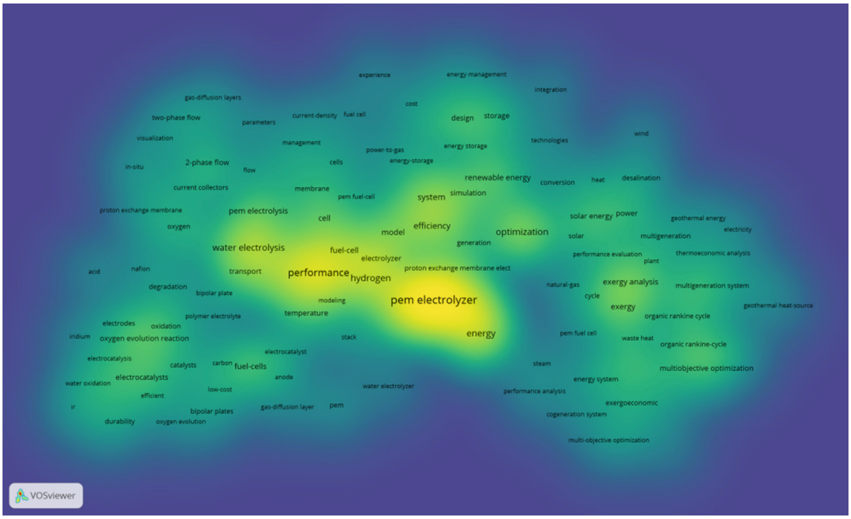


Fig. 11. Heat map of keywords in 2020

Based on the chosen publications, it should be mentioned that Aimy and Kieran are closely cooperated [32, 39, 40] around porous transport layers research. Meanwhile, Mojtaba and Ehsanolah were deeply co-worked [41–43] on electrolyzer related hybrid system investigation. Ibrahim is one of the greatest researchers who has made a significant contribution on PEM electrolyzer utilizing renewable energy [44, 45]. Marcelo was devoted to improve the electrolysis efficiency through novel components and operating conditions [46, 47]. These researchers have carried out their previous research directions in the past three years.

Table 3. Most productive authors in PEM electrolyzer during 2020–2022

Rank	Author	2020	2021	2022	Summary
1	Guilbert, Damien	5	3	0	8
2	Bazylak,Aimy	4	2	0	6
3	Alirahmi, Seyed Mojtaba	2	1	3	6
4	Fahy, Kieran F.	3	2	0	5
5	Assareh, Ehsanolah	0	1	4	5
6	Dincer, Ibrahim	1	3	1	5
7	Carmo, Marcelo	2	1	2	5
	Summary	17	13	10	40

Damien engaged in electrolyzer modeling and experimental verification for several year. His latest publication on 'Journal of Processes' in 2021 turn to study electrolyzer related testing applications [48]. This slightly variation maybe signify the further development of electrolysis related technology in application level.

Journal statistics help researchers choose the most suitable journal for their work. The publication Journal clusters show a clearly verification for the chosen publications, changing from 'Journal of International Journal of Hydrogen Energy' into other Journals instead, such as Energies and sustainable energy technology, which can easily be seen in Fig. 12.

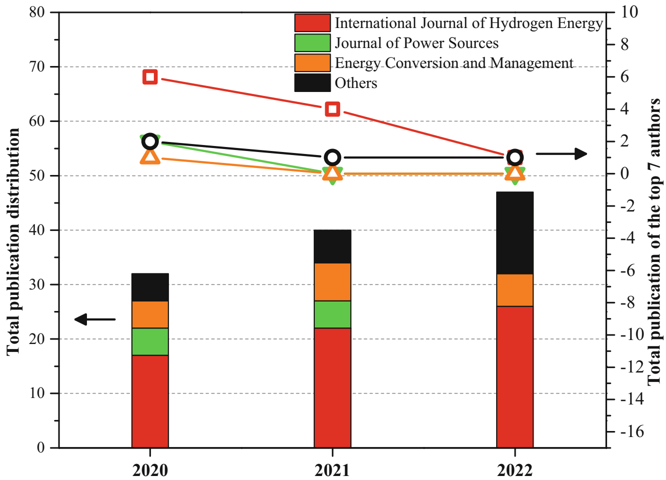


Fig. 12. Analysis of publication journals

However, even the weight of 'International Journal of Hydrogen Energy' among the articles significantly decreased, this Journal is still the mainly journal for publishing work about PEM electrolyzer for most researchers. Data analysis indicates that some Journals, such as Sustainable Energy Technologies, Journal of Power Sources, Energies, are becoming more attractive to the related research. This phenomenon maybe related to the transfer of the research topics of the journals, so that gives authors more choices (Fig. 13).

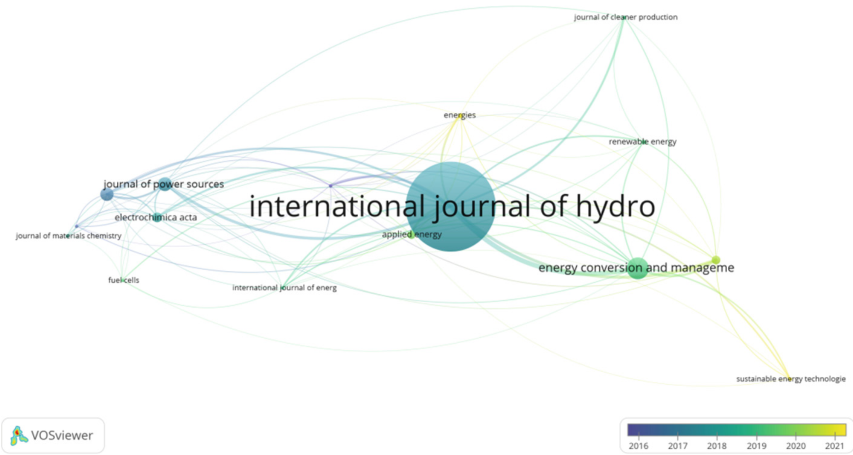


Fig. 13. Overlay visualization of journals co-occurrence year (*Notes* the size of the nodes is weighted by publications)

5 Conclusion

Based on the bibliometric analysis of the 411 PEM Electrolyzer publications released between 2005 and 2022, it is found that the research has increased explosively with the Iran being the leading producer, especially in recent 5 years. China lacks top scholars and core leader in the field. Most researchers have stable cooperative relationships, and continues their research direction in recent years. Component and hybrid system related study are investigation hot-spots recently. Furthermore, keywords including two phase flow and geothermal hybrid systemare more concerned than ever. More journals are joining the publications about hydrogen, but the status of the main journal (International Journal of Hydrogen Energy) is still unshakable.

Overall, electrolysis is a novel production method for clean energy. Bibliometrics is a useful tool to discover the current research hot-spots and future trends of a field. PEM electrolyzer related analysis in this paper clearly exhibits the research topic modification and research trend in recent years. This paper is hoping to offer beneficial inspirations and new frontiers for relevant scholars.

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