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A Bibliometric Analysis and Evaluation of Hydrogen Energy: The Top 100 Most Cited Studies

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Abstract: This study investigates the contribution of highly cited researchers around the world in the field of hydrogen energy. The main aim is to examine the trend in the hydrogen energy field and provide quick and easy access to researchers. In this context, a comprehensive bibliometric approach has been applied to visualize the scientific publications about hydrogen energy which are guiding the literature and are highly cited according to the web of science (WOS) database. Several aspects of the top 100 highly cited studies have been analyzed such as publication type, fundamental research areas, productive journals about the issue, citations, authorship pattern, affiliations, most used keywords, most used words in abstracts, etc. Besides, the contributions of countries, institutes, authors, and journals have been shown. It is found that the University of Miami has a great impact on hydrogen energy with 9 articles in the top 100 highly cited articles. The most productive author has been determined as Turhan Nejat Veziroğlu with 9 articles. When the 100 most cited articles on hydrogen energy are analyzed, the USA is the leading country with 31 studies. Despite some flaws, this trend subject study identifies the most important contributions to hydrogen energy research over the years and reveals many important scientific breakthroughs and highlights that have taken place over this period. In addition, this article is thought to have great help and guidance to researchers who want to investigate hydrogen energy.

Keywords: bibliometric analysis; hydrogen energy; hydrogen storage; hydrogen production

Hidrojen Enerjisinin Bibliyometrik Analizi ve Değerlendirilmesi: En Çok Atıf Alan İlk 100 Çalışma

Öz: Bu makale, dünya çapında hidrojen enerjisi alanındaki yüksek atıf alan araştırmacıların katkılarını araştırmaktadır. Temel amaç, hidrojen enerjisi alanındaki trendi incelemek ve araştırmacılara hızlı ve kolay erişim sağlatmaktır. Bu kapsamda hidrojen enerjisi ile ilgili literatüre yön veren ve Web of Science (WOS) veri tabanına göre yüksek atıf alan bilimsel yayınları görselleştirmek için kapsamlı bir bibliyometrik yaklaşım uygulanmıştır. En çok atıf alan 100 çalışmanın yayın türü, temel araştırma alanları, konuyla ilgili verimli dergiler, enstitüler, yazarlar ve dergiler gösterilmiştir ayrıca alıntılar, yazarlık modeli, üyelikler, en çok kullanılan anahtar kelimeler, özetlerde en çok kullanılan kelimeler vb. gibi çeşitli yönleri analiz edilmiştir. Miami Üniversitesi'nin en çok atıf alan 100 makale içinde 9 makale ile hidrojen enerjisi üzerinde büyük etkisi olduğu tespit edilmiştir. En üretken yazar 9 makale ile Turhan Nejat Veziroğlu olarak belirlenmiştir. Hidrojen enerjisi ile ilgili en çok atıf alan 100 makale incelendiğinde, ABD 31 çalışma ile lider ülke konumundadır. Bazı kusurlara rağmen, bu bibliyometrik çalışma, yıllar içinde hidrojen enerjisi araştırmalarına yapılan en önemli katkıları belirlemekte ve bu dönemde gerçekleşen birçok önemli bilimsel atılımı ve öne çıkanları ortaya koymaktadır. Ayrıca bu makalenin hidrojen enerjisini araştırmak isteyen araştırmacılara büyük bir yardım ve yol gösterici olacağı düşünülmektedir.

Anahtar Kelimeler: bibliyometrik analiz, hidrojen enerji, hidrojen depolama, hidrojen üretimi

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1. Introduction

Due to the gradually decreasing fossil energy reserves in the world, it is becoming more and more difficult to meet the ever-increasing energy demand. In addition, fossil energy use generates many emissions, causing serious damage to nature. Thus, providing renewable and clean energy resources for meeting the world's energy demand is an indispensable subject. One of the solutions that can cure this problem is hydrogen, which was found by Cavendish [1, 2]. Hydrogen is one of the energy sources that can provide energy without creating greenhouse warming and environmental pollution. Hydrogen is considered the most promising energy source and the ultimate tool for solving environmental and energy crises in the 21st century [3, 4]. However, research mostly shows that, under current circumstances, hydrogen is about two to three times more expensive than other traditional fuels, and its use as a common energy source strongly depends on cost-cutting technological advances in hydrogen production. It is precisely for this reason that most studies on hydrogen energy have focused on overcoming these difficulties. Considering the hydrogen energy, it is possible to encounter many sub-topics. For example; hydrogen production methods (electrochemical, thermochemical, photochemical, photocatalytic, photoelectrochemical, photo biological processes, etc.) [5–8], hydrogen storage and transport [9, 10], materials for hydrogen storage [11–16], hydrogen economy [17, 18] and much more. Combustion of hydrogen does not produce CO_2, CO, SO_2, and VOC but it entails steam and NO_x emissions. Therefore, considering its environmental perspective, hydrogen is a very clean energy source. There is much recent research [19–22] and review studies [23–26] on the hydrogen energy subject and new studies are being done every day. Undoubtedly, all of them are very important and useful. However, since they are generally related to one of the specific sub-topic we have mentioned above, it is difficult to see what direction the whole trend is and what topics are being studied more and get more citations. In such cases, we think that bibliometric visual studies are very important due to their power that shows which topics are trending in a field. In addition, it is important because it shows the most important articles in this field collectively to the researchers who started working on a field and gives information in terms of all other data. Bibliometric studies continue to be found in different fields of engineering and social sciences [27–30]. Tsay [31] analyzed bibliometric studies on hydrogen energy between 1965 and 2005. However, it is thought that a new bibliometric analysis is needed since many years have passed. Conducting a classical citation analysis or finding the most cited articles on hydrogen energy can contribute significantly to exhibiting up-to-date academic knowledge, progress, and trends in this regard. In this study, we systematically analyzed the 100 most cited articles in the field of hydrogen energy (T100) based on data from the Web of Science (WoS). In this study, we analyzed total citations, average citations per year (ACpY), citations and publications by years, productive journals, institutions of origin, countries of origin, the most common topic of frequently cited articles, and the collaboration of the authors, and much more.

2. Data Collection and Method of Data Analysis

The data used in this bibliometric analysis were acquired from the Thomson Reuters WoS Core Collection database (Philadelphia, Pennsylvania, USA). We accessed the WoS database on May 9, 2020, between 1975 and 2020, using the keyword "hydrogen energy". As a result, we obtained 26942 articles and analyzed the 100 most cited articles among these results. Articles not directly related to "hydrogen energy" were excluded; only original research papers, review papers and conference papers have been included. All of our authors independently identified and agreed on the first 100 articles cited and directly related to hydrogen energy. In this study, we used the average citation per year (ACpY) values derived from WoS as a factor in time, since it is likely that older articles have more citations than newer ones. Some of the analysis results were created with the VOS program. VOS viewer is a program used to create and visualize bibliometric networks. These networks can include, for example, journals, researchers, or particular publications, and can be created based on

citation, bibliographic matching, co-citing, or co-authoring relationships. VOS viewer also allows the visualization of scientific articles by reading both the keywords and abstract texts with the data mining technique and calculating which word is used statistically. Quantitative analysis of the literature of the top 100 most cited articles can show the international status of global hydrogen energy research from a wide perspective and provide an overview of hydrogen energy.

3. Results and Discussion

The top 100 cited articles and ACpY values are listed in Appendix 1. The article Ni et al. [32] titled "A review and recent developments in photocatalytic water-splitting using TiO_2 for hydrogen production" published in Renewable and Sustainable Energy Reviews (2007, 11(3), pp. 401–425) has the highest number of citations (n = 2607) and highest ACpY (n = 200,54). The authors stated that nanoscale photocatalytic water splitting technology is low cost and ecologically friendly and also has great potential considering the hydrogen economy. The second and third most cited publications were seen by Sakintuna et al. [11] (n=1973) titled "Metal hydride materials for solid hydrogen storage: A review" and Carmo et al. [33] (n=1361) respectively, but it was determined that the ACpY value of Carmo et al. (n=194,43) was more than Sakintuna et al.'s (n=151,77). Sakintuna et al. [11] examined metal hydrides in terms of their physical properties besides hydrogen storage capacity to overcome the difficulties in hydrogen storage. Carmo et al. [33] aimed to reveal the current state of the art and challenges of PEM electrolysis technology by addressing the challenges associated with electrocatalysts, solid electrolytes, current collectors, separator plates, and modeling efforts for hydrogen production. The language used in all the top 100 articles in English. When the 100 most cited articles on hydrogen energy were examined it was seen that more than half of them were research articles contrary to the general opinion (Fig. 1).

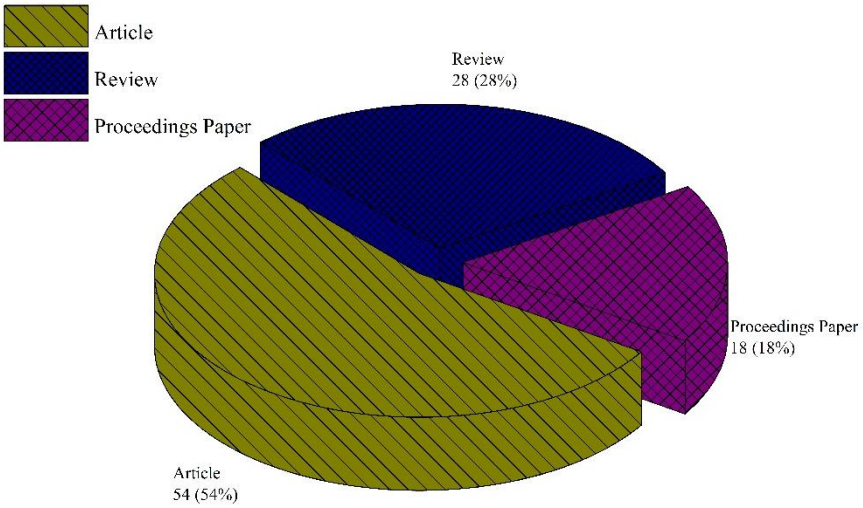

Figure 1. Types of most cited 100 articles

When we examine the top 100 most cited articles on hydrogen energy, it was seen that these articles were mostly in the Chemistry Fuels and Chemistry Physical categories according to WOS data and then the electrochemistry category (Fig. 2). While WOS is analyzing this data, there may be some duplicate counts as it sometimes places the same article in multiple categories.

When the top 100 articles cited about hydrogen energy subjects and the most cited articles were examined as in Fig. 3, it was seen that these publications, which received the most citation, started in 1998 (4 publications). It was observed that the number of articles published in 2002 (14) was the highest and the number of citations increased close to linear, especially between 2000 and 2011.

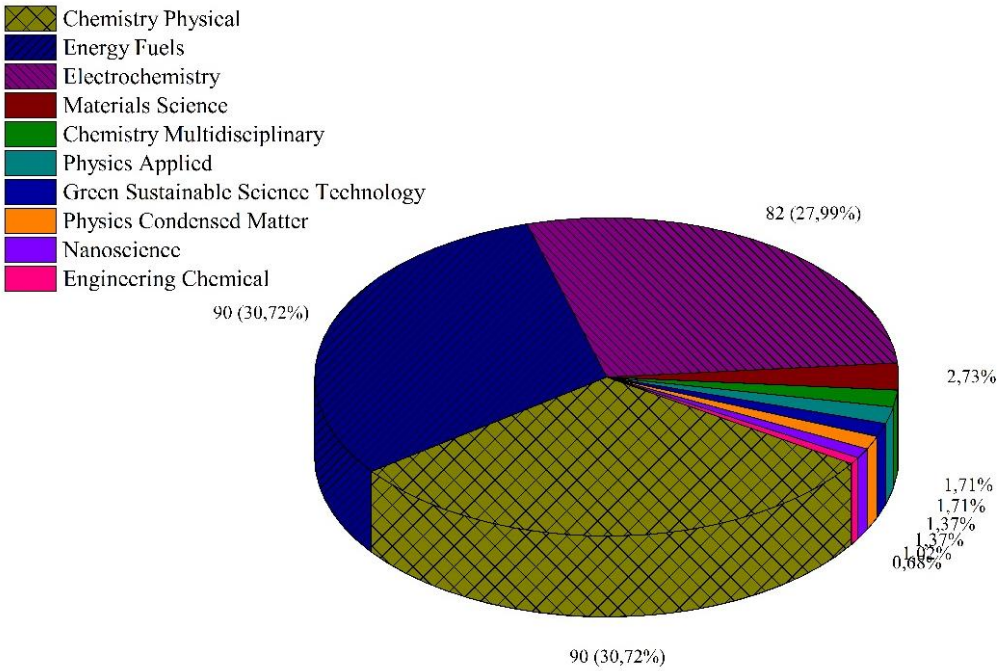

Figure 2. Categorization of top 100 hydrogen energy articles according to the WOS data

There was no publication published in 2011 and included in the top 100 list. Although the number of citations increased between 2011 and 2017, the number of publications receiving the most citations did not increase much. Since journals' publication evaluation process is sometimes prolonged, a certain amount of time needs to pass before the publications can be cited.

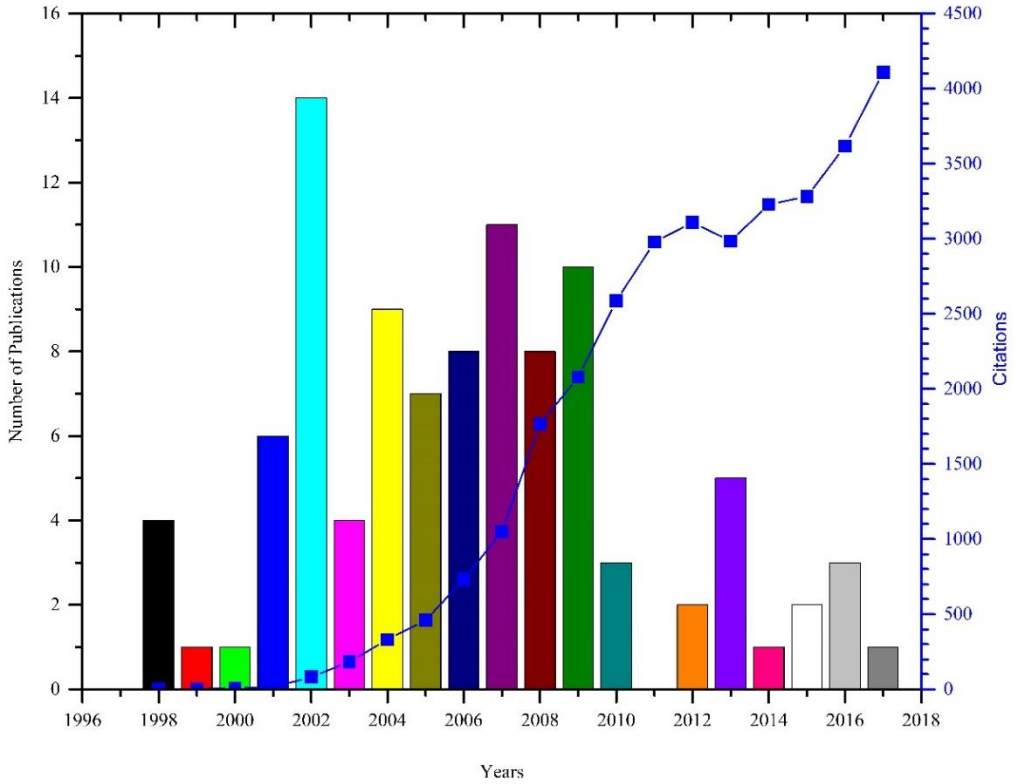

Figure 3. Published the top 100 articles and total citations in each year (1998-2017)

As is seen in table 1 most of the articles were published in the "International Journal of Hydrogen

Energy" due to the journal's name being integrated with the subject. However, as we mentioned in the introduction part since hydrogen energy is related to many sub-topics (hydrogen production, material, economy, environment, chemistry, etc.), there have been studies that have included many cited articles from different journals.

Table 1. List of journals that published the most cited hydrogen energy articles

Rank	Journal	Number of articles	Impact Factor*	Country	JCR Category
1	International Journal of Hydrogen Energy	82	4.084	England	Q2
2	Renewable & Sustainable Energy Reviews	3	10.556	England	Q1
3	Nature Materials	2	38.887	England	Q1
4	Advanced Functional Materials	1	15.621	Germany	Q1
5	Advanced Materials	1	25.809	Germany	Q1
6	Annual Review of Energy and the	1	1.154	USA	Q2
7	Carbon	1	7.466	England	Q1
8	Chemsuschem	1	7.804	Germany	Q1
9	Energy	1	5.537	England	Q1
10	Energy Environmental Science	1	33.250	England	Q1
11	Industrial & Engineering Chemistry Research	1	3.375	USA	Q1
12	Journal of Alloys and Compounds	1	4.175	Switzerland	Q1
13	Journal of Materials Chemistry A	1	10.733	England	Q1
14	Journal of the American Chemical Society	1	14.695	USA	Q1
15	Nano Energy	1	15.548	Netherlands	Q1
16	Solar Energy	1	4.674	England	Q1

* 2018 Journal Citation Reports® (Clarivate Analytics)

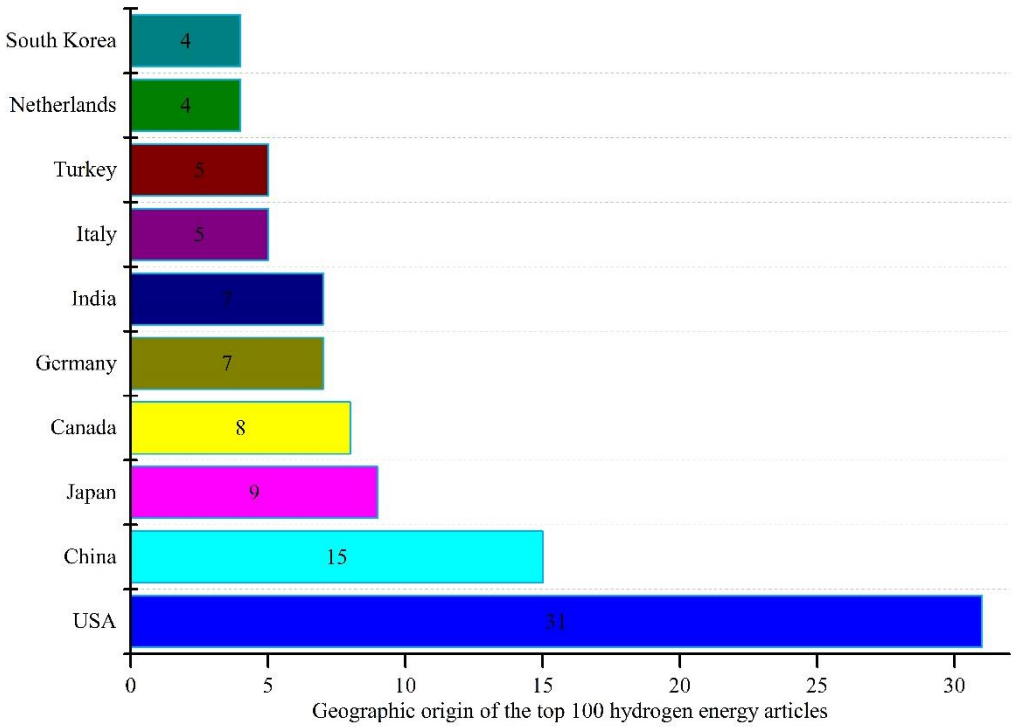

Figure 4. Geographic origin of the top 100 hydrogen energy articles

Citations and publications analyzes have been carried out among the top 100 articles. A minimum number of a document of a country is set to 1 and 28 countries have been found. For each of the 28 countries, the total strength of the citation links with other countries has been calculated. The countries with the total link strength have been selected. In this context, the USA has been found a

place with 30 articles and 11997 citations with total link strength of 78. Then, China has 15 articles with 7771 citations and total link strength of 37. After that, Japan has 9 articles with 3306 citations and total link strength of 12. Canada has 8 articles with 3467 citations and total link strength of 43. In the following, Germany and India have 7 articles and 4882 and 3243 citations, respectively. The number of publications in the top 10 countries can be seen in Fig. 4 and the correlation between citations and total link strength has been illustrated in Fig. 5.

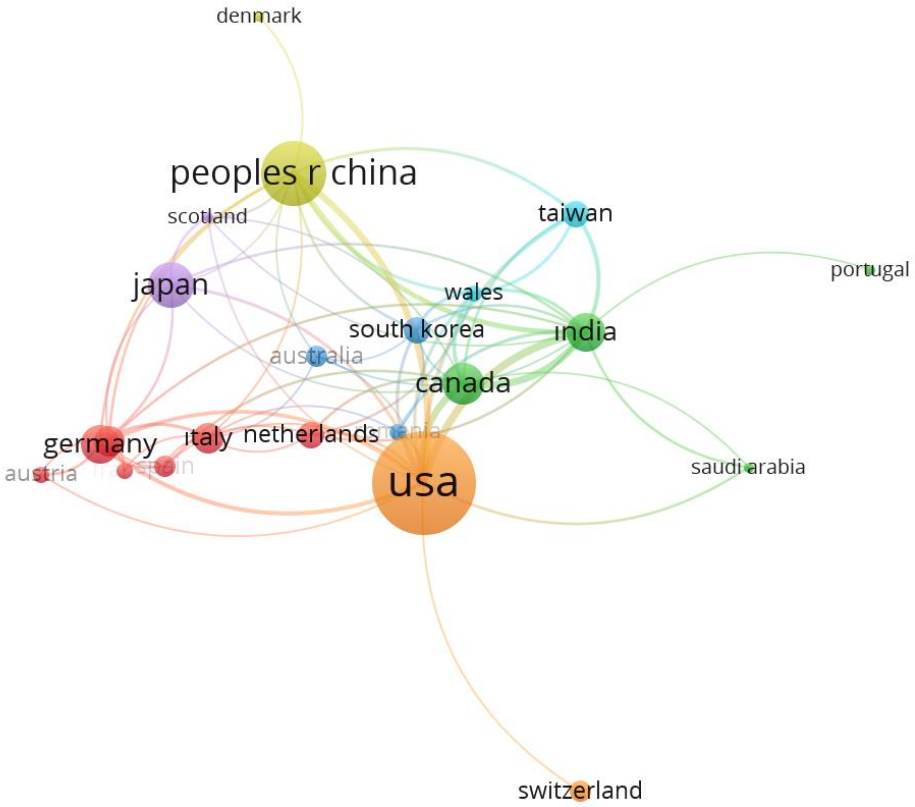

Figure 5. Geographic origin of the top 100 hydrogen energy articles and their citation interop connections

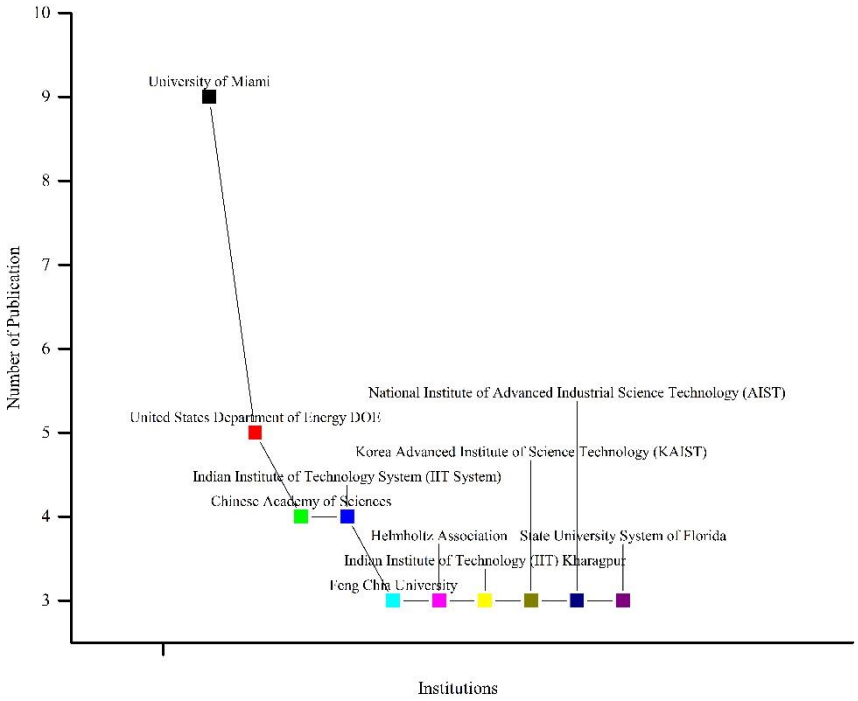

Figure 6. Institutions of origin of the top 10 among top 100 hydrogen energy articles

When the top 100 most cited articles on hydrogen energy are analyzed, Miami University ranks first with 9 articles. The top 10 institutes/universities are shown in Fig. 6 below. With 5 articles, DOE is in second place, with four articles, the Chinese Academy of Science and the Indian Institute of Technology System is in third place.

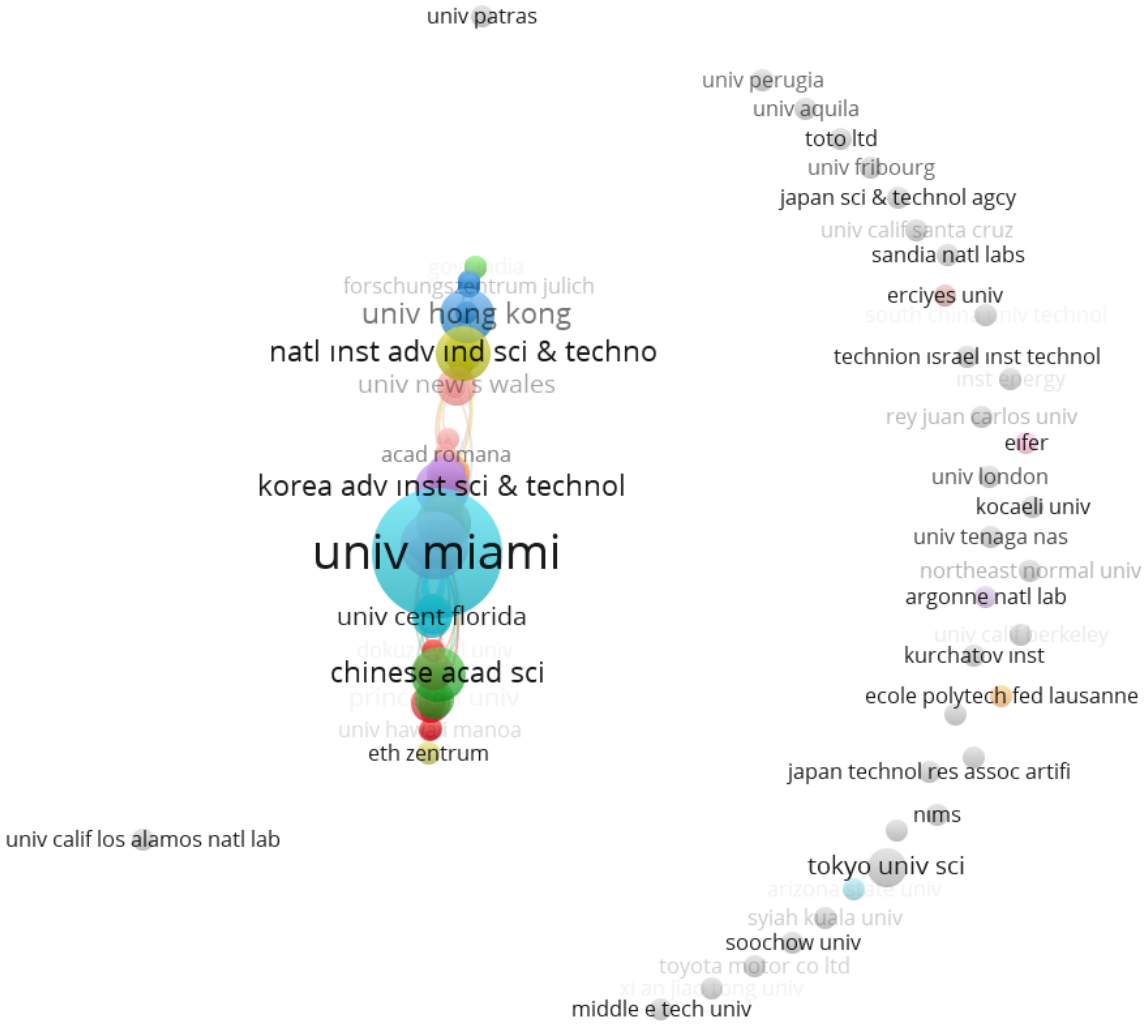

Figure 7. Institutions of origin of the top 100 hydrogen energy articles and their relations

The abstract data of the top 100 most cited articles on hydrogen energy are processed and the most frequently used words and their relationships are visualized in Fig. 8. While doing this analysis, only the abstract section is handled, structured abstract labels are ignored and copyright statements are also ignored. The counting method has been chosen as full counting instead of binary counting. A minimum number of occurrences of a term is considered to be 1. When this number of occurrences terms is considered as 10, 28 terms are determined. Among them, hydrogen production (95) took the first place, while fuel (62), catalyst (55), energy (45), reactor (35), reaction (33) were repeated as seen in Fig. 9. As it is known, the abstract of an article provides a quick content evaluation of that article. Therefore, seeing the words frequently used in the abstract of an article allows us to quickly see what keywords and topics are focused on, in addition to providing information about the content.

As it is known, when a literature study is conducted on a subject, searches are carried out on keywords. Therefore, the keywords of an article are closely related to the visibility of the article. Thus, it should be chosen in the right number and should be suitable for the usage density of the literature.

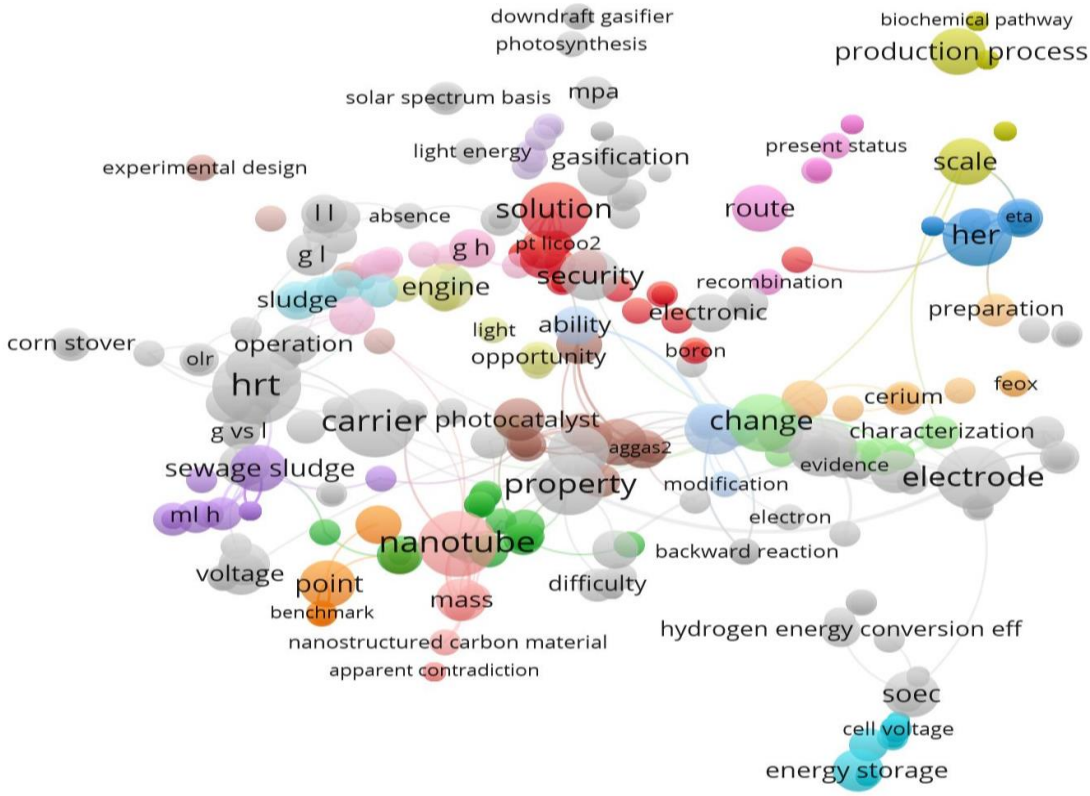

Figure 8. Map-based text data of entire top100 articles abstract field (1 occurrence)

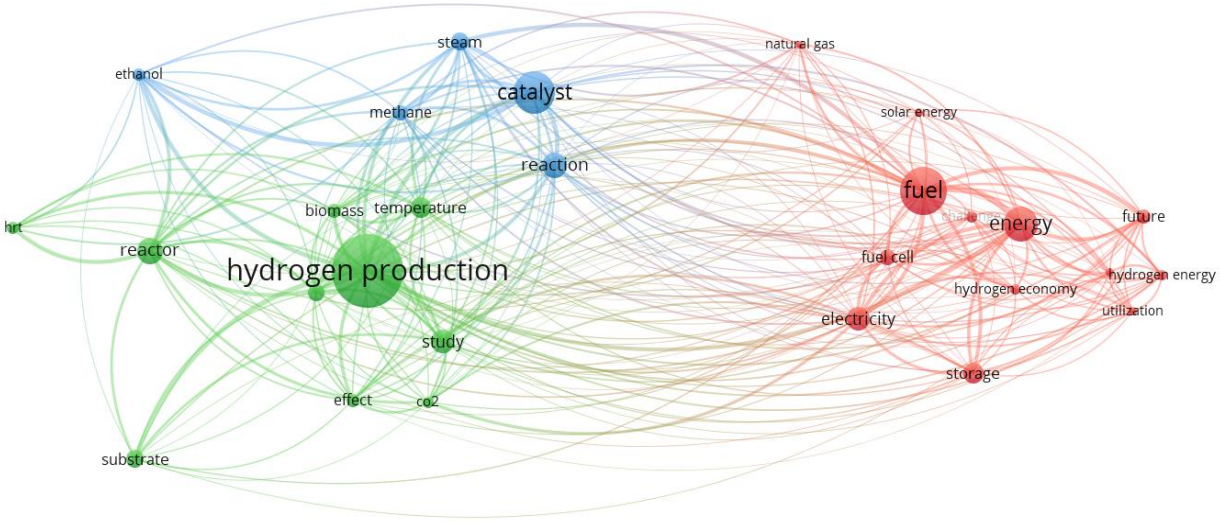

Figure 9. Map-based text data of entire top100 articles abstract field (10 occurrences)

When the keywords of the 100 most cited articles on hydrogen energy were analyzed, it was observed that the keyword "hydrogen" was used 19 times, the keyword "hydrogen production" was used 16 times, the keyword "hydrogen storage" was used 11 times, and the keyword "fuel cells" has been used 7 times. Fig. 10 below shows these keywords and their relationship to each other. The size of the writing character tells us that the keyword is used frequently, and the thickness of the lines between the words has a strong usage bond between them.

When each author is evaluated independently, Veziroglu TN. is the author having 9 articles with the most articles among the 100 most cited articles. Table 2 below shows which authors are in the top 10

and the total citation numbers of their publications on the topic of hydrogen energy only in the top 10.

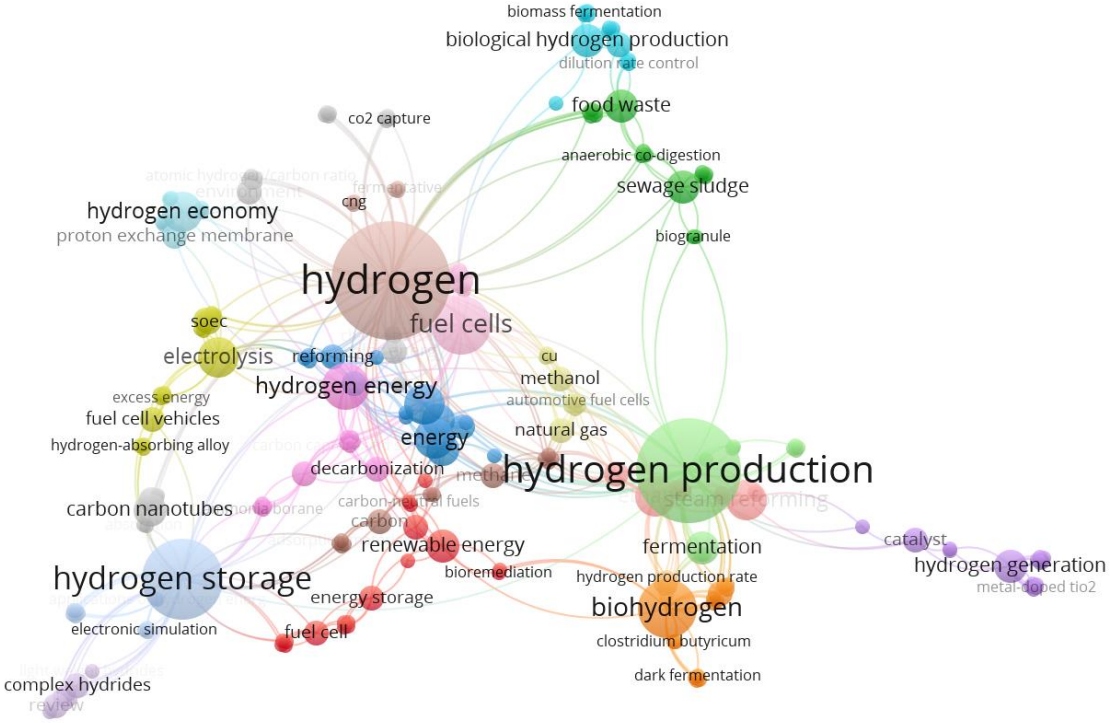

Figure 10. Most used author keywords in top 100 articles

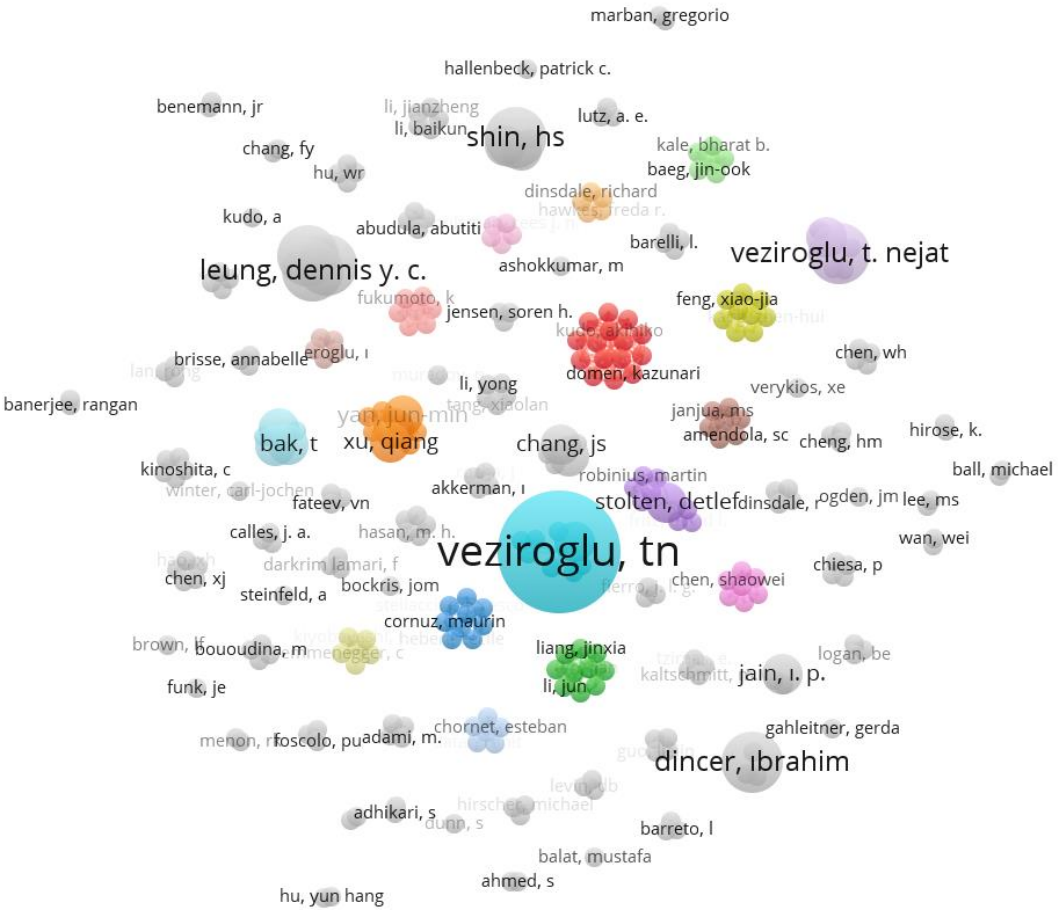

Figure 11. Co-authorship unit of analysis in top 100 articles (for each article)

Table 2. Top 10 most published researchers on hydrogen energy among top 100 highly cited articles

Rank	Author	Number of articles in the top 100	Total Citations (WOS)
1	Veziroglu T.N.	9	4183
2	Das D.	3	2100
3	Dincer I.	3	1057
4	Leung DYC.	3	3794
5	Leung MKH.	3	3794
6	Ni M.	3	3794
7	Shin HS.	3	915
8	Bak T.	2	1394
9	Chang JS.	2	536
10	Dinsdale R.	2	1074

A map of co-authorship has been provided in Fig. 11 by full counting of the entire top 100 articles. 309 authors have been found in this regard. Clusters show which authors work together. The size of the colored circles also shows that they have a relatively large number of articles.

4. Strengths, Limitations, and Future Directions

The strength of this study is to provide fast and direct access based on 100 articles that are most cited to identify hydrogen energy trends and current information on hydrogen energy without requiring advanced statistical methods. On the other hand, only the total number of citations is presented in this study, and it is a subjective constraint for performing citation-based bibliometric analysis, proving the quality of the research, determining the number of publications by years, and also evaluating the author's scientific efficiency or h-index. Also, the results of our work using the WOS database may vary if other databases are used. Unlike advanced research methods, occasional bibliometric analyzes for different engineering disciplines and subfields show developments in these fields from a nominal perspective. Data from existing studies can provide cost-effectiveness in planning and financing future research projects. In the last decade, approaches that are defined as altmetrics and which include multiple evaluations that also measure the power of scientific studies on social media are becoming increasingly popular and offer a different evaluation preference. In future studies, this altmetric approach can also be studied in terms of quantitative analysis.

5. Conclusion

Hydrogen is not a natural fuel, it is a synthetic fuel that can be produced from different raw materials such as water, fossil fuels, or biomass by utilizing primary energy sources. Many alternative hydrogen production technologies such as purification of waste gases, electrolysis, photo processes, thermochemical processes, and radiolysis are used during the production phase. The fact that the produced hydrogen can be transported by pipelines or ships over long distances without encountering big obstacles facilitates its use and distribution. On the other hand, the disadvantage of hydrogen energy can be considered as the cost of high purification of hydrogen, the need for liquefaction due to the large volume needs, and the associated high pressure and cooling problems. When the literature is already examined, it can be seen that the researchers focus on the studies aimed at eliminating the disadvantages of actually an advantageous situation. Examining the pioneering works of the literature on a subject is undoubtedly useful in understanding and revealing the state of the art. For this reason,

in this study, we examined the top 100 most cited articles that are closely related to the hydrogen energy issue, quantitatively and visually in detail. We have revealed the types, categories, and several citations, authors, countries, a network of research cooperation, keywords, and data mining of abstracts, and also revealed which journals are pioneers, impact factors, countries, and many more of these 100 articles. We think that we provide a wide perspective to researchers that want to study the subject.

Authors' Contributions

VB designed the structure and has undertaken the acquisition, processing, and visualization of the data of the article. Also, VB wrote up the article. YÜ is the supervisor of the study.

Both authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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