

Renewable energy: a bibliometric analysis

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Abstract. The aims of this paper are to identify existing research on renewable energy; identify the most influential publications, authors, organizations to understand the research areas. The paper is centered on the bibliometric analysis based on the Web of Science database for the key phrase 'renewable energy' in the article title until 2020. We analyzed the publications about renewable energy by years, by research areas, by geography, by research organizations and research sponsors, by journals, by citations of journals, authors, publications, co-occurrence by keywords. Analysis of the most cited publications and authors, analysis of co-occurrence by keywords was performed using VOSviewer. We performed hierarchical cluster analysis, and clusters were selected using VOSviewer. We found 17805 scientific publications on renewable energy published in scientific journals (51.7% of publications were published during 2016-2020). The most popular research areas are energy fuels, engineering, science technology, environmental sciences, ecology, and business economics. The majority of papers was published by the scientists from the United States, China, and India. In addition, we identified six main research clusters. They are related to an optimizer, renewable energy, biomass, co2 emissions, model, desalination. *Conclusions:* This analysis confirmed the author's hypothesis about the definition of new scientific horizons of renewable energy research. Our results can help scientists interested in renewable energy looking for research funding and research project risks based on renewable energy.

1 Introduction

All over the world, the study of renewable energy draws interest of various scientific schools, economics, and especially stakeholders, who can benefit from the use of renewable energy technologies [1–7]. Resource constraints, sustainable energy, biomass, co2 emissions make it possible to establish the hypothesis of the transfer of scientific interests from energy fuels and environmental sciences ecology to other areas. The definition of the role and place of renewable energy in business economics, mechanical engineering, science technology and compute science is gaining more and more popularity [8–17].

In addition, the essential study of modern scientific schools on renewable energy has a number of patterns, confirming that it is possible to obtain sound theses to determine the

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features of optimization of financial, intellectual and labor resources in the development of renewable energy research in modern space [18–23].

Modern energy systems are undergoing a revolutionary change. Significant influence on these changes is lobbied by various organizations of world importance and economically developed countries [24–26]. We are currently observing:

- adjusting the operation of more flexible architectures of energy systems;
- development of intelligent networks and their interaction with energy storage and use technologies;
- scaling the market of active consumers, for whom the origin of energy is important;
- reorganization of the electricity market and development of cloud technology technologies, energy net.

But not in all countries you can see support for the development of renewable energy. Although these areas of research and implementation at the industrial level can be actively promoted in the digital environment [27–29]. In this paper, we aim to examine the place of renewable energy in various areas of research [30–34], as well as to identify the relationship between renewable energy and economic aspects. The main objectives of this study are to substantiate the following assumptions:

1. Renewable energy research vectors are moving towards business economics. The economic benefits of implementation and the financial risks that businesses may incur during the implementation of renewable energy projects are becoming an increasingly important issue.

2. The issue of renewable energy is interesting to absolutely all countries and the geographical location of scientific schools should be ignored. It is more appropriate to emphasize the study of research sponsorship, ie those stakeholders who may later become the owners of these studies results.

3. There is a subjective statement that renewable energy is more related to CO2 emissions and their system of optimizing storage and using. Modern researchers are already paying more attention to such issues as desalination, hydrogen energy, power electronics, biomass.

Therefore, our research focuses on the peculiarities of the development of research in the field of renewable energy, and determining the patterns of this issue.

The main direction of this paper is bibliometric analysis of the scientific literature on renewable energy. It allows to form a holistic view of existing research on selected topics, to identify the most influential publications, authors and organizations, to analyze the directions of existing and future research.

The aim of the work is to analyze existing research of renewable energy, to identify the most influential publications, authors, organizations patterns of development research areas.

This study analyzes the impact of journals, authors and articles, analyzes research areas, research geography, renewable energy organizations and sponsors such studies. In the end of the article the analysis of co-occurrence by keywords and recommendations for possible further research is proposed.

2 Materials and methods

At the beginning of the analysis, the methods used for bibliometric analysis [35–38] were analyzed. As a result, the analysis application of the most cited publications and authors, analysis of co-occurrence by keywords using the program VOSviewer was selected. To do this, we first selected all scientific publications on renewable energy based on the Web of Science database for the keyword phrase "renewable energy" in the article title until 2020 inclusive. 17805 scientific publications were found.

Based on 17,805 publications found in the Web of Science database, a sample of 2,000 publications was formed. All publications were sorted by the number of citations from the

largest to the smallest, the first 2000 publications were included in the sample as the most relevant (probability 95%, confidence interval 2.06%).

It was analysed of several sets of publications on renewable energy by years (1974-2020), by research areas, by geography, by organizations that conduct research and sponsor research, by publications, by citations of publications, authors, publications, co-occurrence by keywords. For each indicators it were identified the ten most popular fields of research, countries, organizations, publications, authors, publications, which were displayed using graphical and tabular methods.

It was performed the hierarchical cluster analysis and it were selected clusters using VOSviewer based on keywords. Keywords with more than 45 repetitions excluding geographical names were selected, a sample of 2000 publications from the Web of Science database (95% probability, 2.06% confidence interval).

3 Results and discussions

Carrying out bibliometric analysis and searching for scientific publications on issues related to the energy system is the key to the formation of a system removing communication and organizational barriers to stakeholders' interaction. In order to properly construct these approaches, 17805 scientific publications (articles, reviews, book sections, abstracts, etc.) published during 1974–2020 were found in the Web of Science database, primarily for the analysis of renewable energy publications. The number of publications by year is presented in Fig. 1.

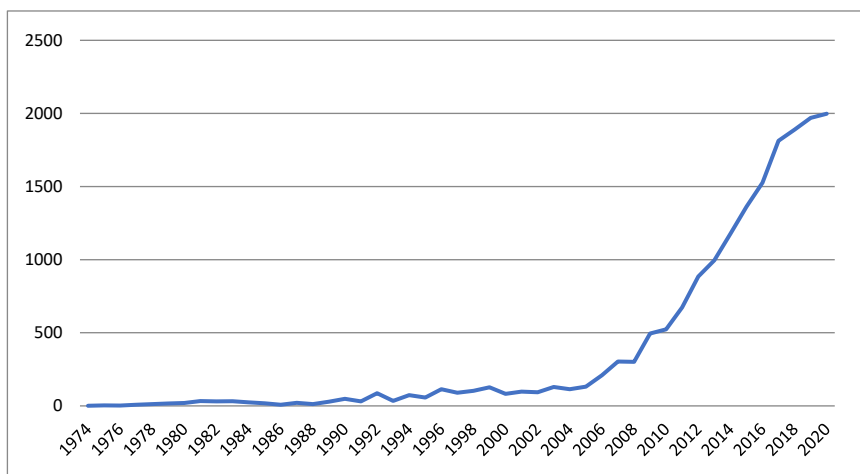


Fig. 1. Number of publications on renewable energy by years based on the Web of Science database (created by the authors)

As can be seen from Fig. 1, 51.7% of publications were published during 2016-2020, which indicates a relatively recent increase in research in this area.

Research on renewable energy is being studied by scientists in various fields of application. The ten most popular areas of research are presented in Fig. 2.

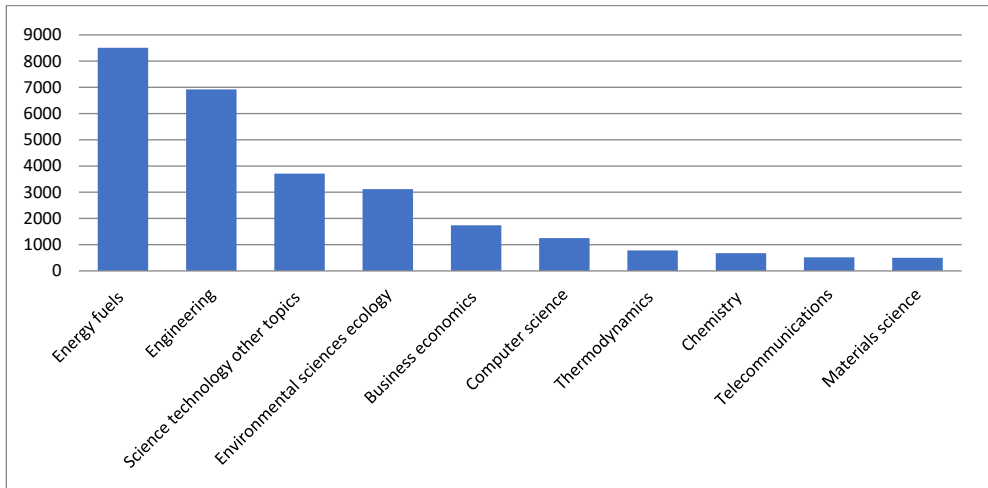


Fig. 2. The most popular areas of research based on the Web of Science database (created by the authors)

As can be seen from Fig. 2, most research concerns Energy fuels (47.8%), Engineering (38.9%), Science technology other topics (20.9%), Environmental sciences ecology (17.5%) and Business economics (9.8%).

Researchers from around the world deal with renewable energy issues. In fig. 3 presents the countries whose scientists have written the most scientific works.

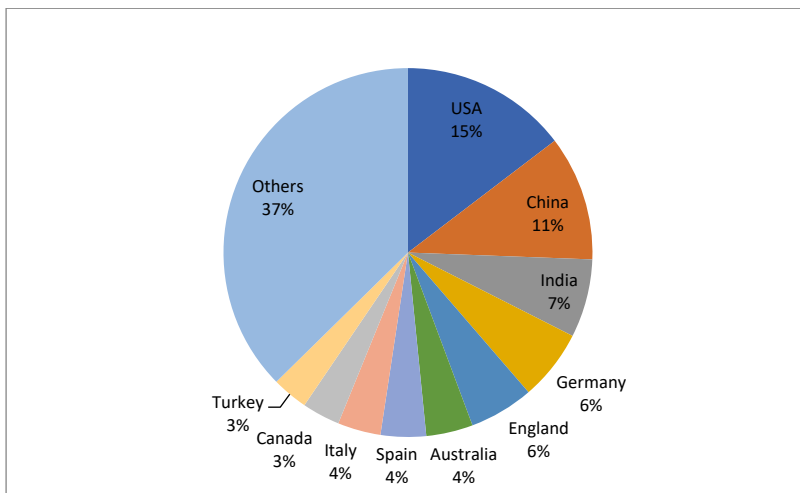


Fig. 3. Number of publications on renewable energy by country based on the Web of Science database (generated by the authors)

As can be seen from Fig. 3, most papers have been published by researchers from the United States (2606 papers), China (1951 papers) and India (1223 papers). At the same time, in some regions, including Ukraine, this topic is insufficiently studied (59 works).

More than 500 organizations conduct research on selected topics. The ten organizations that conduct the most research on selected topics are presented in Fig.4.

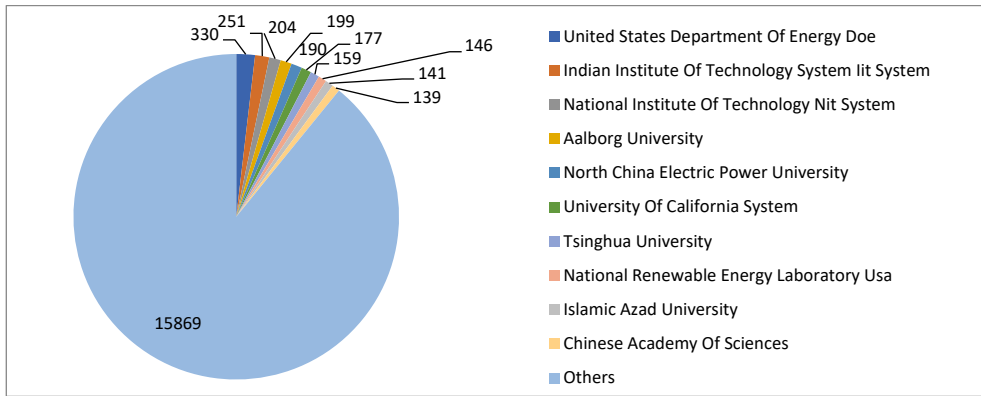


Fig. 4. The organizations that conduct the most research on the basis of the Web of Science database (formed by the authors)

According to Fig. 4, the most renewable energy issues are dealt with by the United States Department of Energy Doe (1.9%), Indian Institute of Technology System Iit System (1.4%), National Institute of Technology Nit System (1.1%), Aalborg University (1.1%), North China Electric Power University (1.0%).

The research is sponsored by more than 500 organizations. In Fig. 5 presents the ten organizations that most often invest in the development of research of renewable energy.

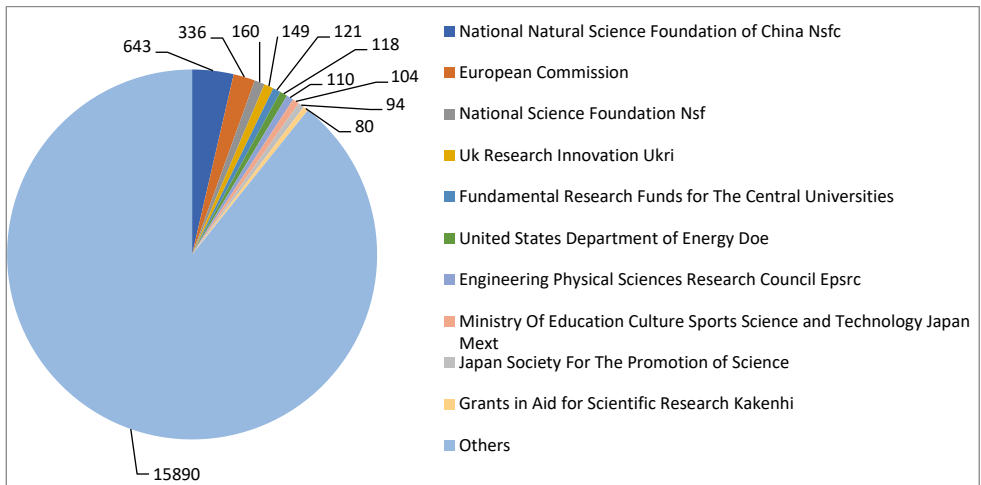


Fig. 5. Organizations that sponsor renewable energy research based on the Web of Science database (created by the authors)

The most frequent sponsors of the research are the National Natural Science Foundation of China Nsfc (3.6%), the European Commission (2.1%), the National Science Foundation Nsf (0.9%) and Uk Research Innovation Ukri (0.8%). (Figure 5).

Renewable energy publications were published in more than 100 publications, with almost a quarter of all publications were published in ten journals (Figure 6).

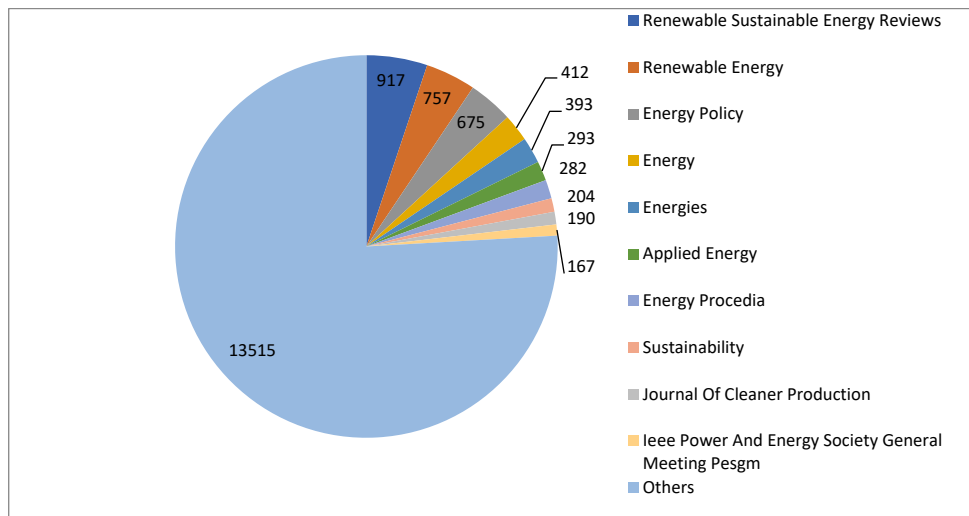


Fig. 6. Journals with the largest number of publications by country based on the Web of Science database (created by the authors)

The most popular magazines are "Renewable Sustainable Energy Reviews" (5.2%), "Renewable Energy" (4.3%), "Energy Policy" (3.8%), "Energy" (2.3%), "Energies". (2.2%). It can indicate the influence of these publications on selected topics.

To determine the influence of journals, we analyzed citations. The most cited publications with at least five publications are presented in Table 1.

Table 1. The most cited publications on renewable energy based on a sample from the Web of Science database (created by the authors)

Journals	Number of citations	Number of publications
Renewable Sustainable Energy Reviews	43720	443
Energy Policy	22471	227
Renewable Energy	13317	180
Energy	9041	116
Applied Energy	8602	100
Ieee Transaction on Industrial Electronic	4412	20
Energy Economics	4119	41
Energy Conversion and Management	3503	47
International Journal of Hydrogen Energy	2720	26
Ieee Transaction on Power System	2401	19

Thus, both lists includes only five publications: Renewable Sustainable Energy Reviews, Energy Policy, Renewable Energy, Energy and Applied Energy. It indicates their impact on the subject.

In order to determine the most influential scientists in the chosen field, we identified the most cited authors. The most cited authors with at least five publications are presented in Table 2.

Table 2. The most cited authors on renewable energy based on a sample from the Web of Science database (generated by the authors)

Authors	Number of citations	Number of publications
Lund H.	5898	23
Mathiesoen B.V.	2825	8
Connolly D.	1992	6
Apergis N.	1808	7
Payne J.E.	1755	7
Ozturk I.	1434	10
Walker G.	1310	7
Devine-Wright P.	1300	8
Saini R.P.	1295	12
Blaabjerg F.	1145	6

Each authors has at least six publications, and Lund H. 23 publications that provided the largest number of citations (Table 2). It is indicated the influence of the authors' data on the topic of renewable energy.

Table 3. The most cited articles on renewable energy based on the Web of Science database (created by the authors)

Authors	Title article	Journal	Year of publication	Number of citations
Carrasco J.M. et al. [39]	Power-electronic systems for the grid integration of renewable energy sources: A survey	Ieee Transactions on Industrial Electronics	2006	2237
Panwar N. L. et al. [40]	Role of renewable energy sources in environmental protection: A review	Renewable & Sustainable Energy Reviews	2011	1233
Kempton W & Tomic J. [41]	Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy	Journal of Power Sources	2005	1092
Wuestenhagen R., Wolsink M. & Buerer M.J. [42]	Social acceptance of renewable energy innovation: An introduction to the concept	Energy Policy	2007	1082
Turner J.A. [43]	A realizable renewable energy future	Science	1999	1012
Dincer I. [44]	Renewable energy and sustainable development: a crucial review	Renewable & Sustainable Energy Reviews	2000	902
Banos R. et al. [45]	Optimization methods applied to renewable and sustainable energy: A review	Renewable & Sustainable Energy Reviews	2011	869
Connolly D. et al. [46]	A review of computer tools for analysing the integration of renewable energy into various energy systems	Applied Energy	2010	857

Ellabban O., Abu-Rub H. & Blaabjerg F. [47]	Renewable energy resources: Current status, future prospects and their enabling technology	Renewable & Sustainable Energy Reviews	2014	818
Barton J.P. & Infield D.G. [48]	Energy storage and its use with intermittent renewable energy	Ieee Transactions on Energy Conversion	2014	743

Table 3 shows that all articles were published before 2014, with the oldest article published in 1999.

To understand the areas of research, a co-occurrence analysis was performed by keywords. Figure 7 presents the results of hierarchical cluster analysis with the number of repetitions from 45 except for geographical names in the sample. The sample includes the 2000 most cited publications based on the Web of Science database (95% probability, 2.06% confidence interval).

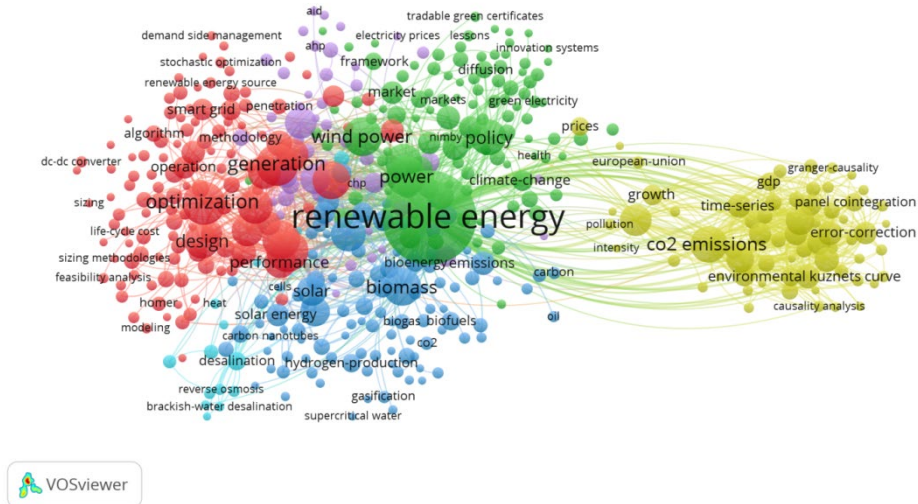


Fig 7. Analysis of co-occurrence by keywords (Web of Science database, sample of 2000 publications, more than 45 keyword duplications excluding geographical names).

Fig. 7 shows that there are six main clusters:

Cluster 1 (123 items): optimizer (Links: 213, Total links straight: 689, occurrences: 116)

Cluster 2 (106 items): renewable energy (Links: 414, Total links straight: 2656, occurrences: 549)

Cluster 3 (102 items): biomas (Links: 200, Total links straight: 529, occurrences: 93)

Cluster 4 (65 items): co2 emissions (Links: 145, Total links straight: 733, occurrences: 86)

Cluster 5 (47 items): model (Links: 167, Total links straight: 353, occurrences: 63)

Cluster 6 (15 items): desalinetion (Links: 70, Total links straight: 145, occurrences: 22).

4 Conclusions

In general, this paper considers the historical development of renewable energy research in different areas: temporal, geographical, authorial, sponsorship of scientific fields, implementation of scientific journals. This approach has identified a few patterns that can justify further research.

The chosen time lag of 45 years showed the relevance of this topic in the last 10 years and allowed to divide the time period into 2 stages. There was a constant interest in the topic (up to 200 publications per year) until 2006. There was intense revitalization of scientists to renewable energy in 2006-2020. Based on this, we can conclude about the relevance of this topic and the fact that in the future it is necessary to more meaningfully study the period 2006-2020 with detailing and make the additional divisions into stages in this time period.

In this work, we were able to confirm the study vector of renewable energy. Indeed, almost 2/3 of all work belongs to energy fuels and engineering. But in the research of this issue, concentrated in the active period of 2006-2020, we saw a trend of increasing research renewable energy in business economics, mechanical engineering, science technology and computer science.

An interesting result of the study concerns the researchers affiliation to the country. We have suggested that the topic of renewable energy is most interesting for economically developed countries that can afford to invest in this area. But the analysis revealed that most of the work has been published by researchers from the United States, China and India. None of the G7 countries, except the United States, is actively involved in the scientific development of renewable energy. It turns out that our assumption about the non-neglect of geographical localization must also be taken into account. Therefore, it is necessary to pay attention to the work of the following research centers: United States Department of Energy, Indian Institute of Technology System IIT System, National Institute of Technology Nit System, Aalborg University, North China Electric Power University.

But the issues of research sponsorship has shown the role of the European Union and the United Kingdom in the study of renewable energy, where they influence research through the European Commission and UK Research Innovation UKRI.

A rather pleasant fact is that the world community is interested in renewable energy issues and actively presents its own results in those journals that are authoritative. And in these 5 magazines more than 80% of all publications of explored authors are published. Authors citation indexes indicate their publications relevance and the renewable energy influencing in general.

Conducting co-occurrence research on keywords allowed us to identify six main clusters related to optimization, renewable energy, biomass, CO₂ emissions, model, desalination. This analysis confirmed the author's assumptions about the definition of new scientific horizons of renewable energy research.

The results can be of value to those scientists who are interested in the topic of renewable energy, especially the prospects for the development of the financial investment rationale, risk research of projects based on renewable energy.

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