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Bibliometric Analysis of the Energy Efficiency Research

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Abstract
Energy efficiency is the central focus of energy policies in many countries, and it is also at the forefront of the debate on energy sustainability. To further understand the research frontiers in the energy efficiency field, this paper utilizes a bibliometric analysis with the help of visualization tools: CiteSpace and VOSviewer. The relevant literature during 2010-2020 is collected with the retrieval formulas from the Web of Science Core Collection. Firstly, this paper analyzes the annual indicators, research areas, productive institutions, authors, and journals of publications to comprehend the temporal and spatial distribution characteristics of the energy efficiency literature. Meanwhile, this paper identifies the productive institutions and authors and the influential journals. Then, we construct the collaboration networks among countries/regions/insti tutions, references, and authors to know the collaborative relationships. By analyzing the keywords from highly cited papers with clustering, timeline view, and time zone view, the trend of changes is grasped over time in the energy efficiency literature. Finally, conclusions and some directions for future research are put forward in terms of the bibliometric analysis findings, which may make some references for researchers in the energy field.

Keywords
Energy efficiency; Bibliometric analysis; Highly cited papers; VOSviewer; CiteSpace

Introduction

Energy efficiency is a term defined as the ratio of useful outputs to energy inputs in a certain process. Energy efficiency is an invisible resource that is difficult to measure. The International Energy Agency (IEA) has played a key role in the development of energy indicators to analyze how energy consumption is linked to human activities and energy efficiency (Luis et al., 2013). Generally, plenty of indicators can be used to monitor changes in energy efficiency, which can be roughly divided into four categories (Patterson, 1996): (1) Thermodynamic: This category is an energy efficiency indicator that is completely dependent on the measurement of thermodynamic science. (2) Physical-thermodynamic: This type of indicator is a mixed indicator in which energy input is measured in thermodynamic units and output is measured in physical units. (3) Economic-thermodynamic: This category is also a hybrid indicator in which energy input is measured in thermodynamic units and output is measured by market value. (4) Economical: This type of indicator is purely based on market value to measure changes in energy efficiency. In other words, inputs and outputs of energy are both measured by currency. The ultimate goal of studying these energy efficiency indicators is to improve energy efficiency and bring greater benefits. At present, there are many ways to improve energy efficiency based on these indicators, which can be divided into two general situations: energy conservation and renewable energy development.

Energy conservation is mainly reflected in reducing energy consumption and energy costs. In the 1980s, the difficulty and barriers of energy conservation for improving energy efficiency were raised (Blumstein et al., 1980). Some scholars continued to study the overcomes and put forward solutions later (Hirst & Brown, 1990; Jaffe & Stavins, 1994). The use of energy management practices has been proposed, but it must be pointed out that for energy companies, the potential to improve energy efficiency through the use of energy management practices depends to a large extent on the scale of companies, type of production, degree of production automation, previous emphasis on energy efficiency in the organization, etc (Backlund et al., 2012). Financial development has promoted technological innovation, and can further promote the improvement of energy efficiency. Especially, Ali et al. (2010) used a conceptual industrial energy efficiency policy framework to solve the problem of low energy efficiency in Thai industries. For energy-intensive manufacturers, Ouyang and Ju (2017) discussed the methods of energy savings under non-coordination and coordination scenarios. For energy service companies, Gabisile et al. (2019) proposed a business model by canvas methodology for creating, delivering, and capturing the value of energy.

In most current energy efficiency literature, the transition to green technologies is seen as a sustainable way to achieve a low-carbon or carbon-free environment. The use of green technologies to develop and research renewable energy also requires strong support and funding from the government (Sun et al., 2019). Renewable energy technologies are the core elements of energy efficiency, and their synergy is equally important. The improvement of energy efficiency requires new innovations and adjustments to regulatory frameworks to accelerate the growth of renewable energy such as wind energy and solar photovoltaic technology. At the same time, emerging infrastructure issues should be paid more attention to (Dolf et al., 2019). Energy efficiency plays an essential role in accelerating the transition to clean renewable energy and achieving global climate and sustainable development goals. (Samuel & Vladimir, 2019) found that energy consumption has a positive effect on greenhouse gas emissions, as well as offshore wind power (Ye et al., 2020). Democracy (Chou & Zhang, 2020), fiscal decentralization (Wang, et al, 2020) and smart cities as well (Cingoski & Petrevska, 2020) also have an impact. Therefore, reducing greenhouse gas emissions depends on advanced energy efficiency that clean renewable energy should be taken into account for use. Enhanced energy efficiency can increase economic competitiveness and job creation and play an important role in supporting global sustainable efforts.

Bibliometric analysis can quantitatively construe the research status for a particular subject through statistical analysis of the existing publications, including authors, keywords, publishing countries/regions, publishing sources, etc., to evaluate the development and potential of one target research area (Tsay, 2008; Wang et al., 2021a). At present, studies involving many research fields have used bibliometric analysis to find out the development of the literature of a target topic, associated with the publishing sources and the cooperation between authors or counties/regions (Yu et al., 2017; Wang et al., 2021b). It is worth noting that bibliometrics is quantitative in essence, and it is used to declare qualitative features. In fact, its main advantage lies in transforming the quality of intangible scientific literature into a manageable entity (Du et al., 2013). Bibliometrics provides an analysis tool that extends from the micro (scholars and institutions) to the macro (national and global) level. In practice, researchers are increasingly turning their attention to the possible role of energy efficiency in meeting the energy demand for sustainable economic growth. If we want to properly formulate energy efficiency policy goals and monitor the progress of improving energy efficiency, it needs to have a general understanding of the specific trends in the energy efficiency literature in recent years and theoretically formulate a reasonable operational definition of energy efficiency. Since this field has developed rapidly in the past 10 years, this paper is motivated to use bibliometrics to analyze the literature on energy efficiency from 2010 to 2020.

To further understand the research hotspots, frontiers, and technology trends in the energy efficiency field, this paper uses bibliometric analysis to grasp the basic characteristics and dynamic changes of the energy efficiency literature. To be more precisely speaking, there are three main contributions of this paper:

(1) Master the temporal and spatial distribution characteristics of the energy efficiency literature by annual indicators, research areas, productive institutions, authors, and journals of publications as a whole.

(2) Establish collaboration networks among interrelated countries/regions/institutions, references, and authors through coupling analysis and co-citation analysis respectively.

(3) The highly cited papers are collected as the research focuses. We analyze the keywords from these publications with clustering, timeline view, and time zone view to grasp the trend of changes over time in the energy efficiency literature.

The rest of the paper is constructed as follows: Section 2 describes the data sources and methods for bibliometric analysis. Section 3 presents the results of bibliometric analysis, including the general analysis of the number, sources and distribution of publications; collaboration networks analysis of country/region/institution, references, and authors; and detailed analysis of keywords in highly cited papers. Finally, some discussions and conclusions are summarized in Sections 4 and 5, respectively.

Material and Methods

Bibliometrics can assess the main characteristics of scientific activities in the research field by applying statistical methods (Broadus, 1987). The objective of the bibliometric analysis is to provide a systematic and visualized overview of the existing publications. Therefore, bibliometric analysis by computational and visual analytic approaches, offers opportunities to improve the timeliness, accessibility, and reproducibility of studies of the literature of a field of research (Li & Xu, 2021). The bibliometric analysis involves statistical methods of bibliography counting to evaluate and quantify the growth of literature for a particular subject (Tsay, 2008).

In this paper, two visual analytic tools, CiteSpace and VOSviewer, are used to visualize. CiteSpace is a visual analysis software that has the function of co-occurrence analysis for different countries/regions, institutions, and authors (Chen, 2004). It can also provide knowledge clustering and distribution, and has been widely used to analyze the potential knowledge contained in the scientific literature (Chen, 2006; Chen & Song, 2019). VOSviewer is a tool used to build and visualize bibliometric networks (Nees & Ludo, 2010). It can build networks based on citations, bibliographic coupling, co-citation, or co-author relationships. Both the tools are based on the Java environment to run. The visual analytic approaches can be displayed as a kind of visualized knowledge graph. Then, three bibliometrics methods are used to present the research status and development trend of energy efficiency literature: General analysis, collaboration networks analysis and keyword analysis.

The data source of this paper is obtained from the Web of Science Core Collection (WoSCC). The retrieval strategies are as follows: Topic search=energy efficiency*; Timespan=2010-2020; Databases=Web of Science Core Collection; Document Type: Articles OR Review articles, and obtained 213,117 publications which include author names, titles, abstracts, published dates, document types, addresses, and cited references. The special character "*" is used at the end of the term to identify restrictions, thereby getting more accurate results. Since highly cited papers and hot papers are representative of the corresponding field, a total of 4,747 publications from 2010 to 2020 were extracted as the data set for the collaboration networks analysis and keyword analysis. The methodology framework of this paper is shown in Figure 1.

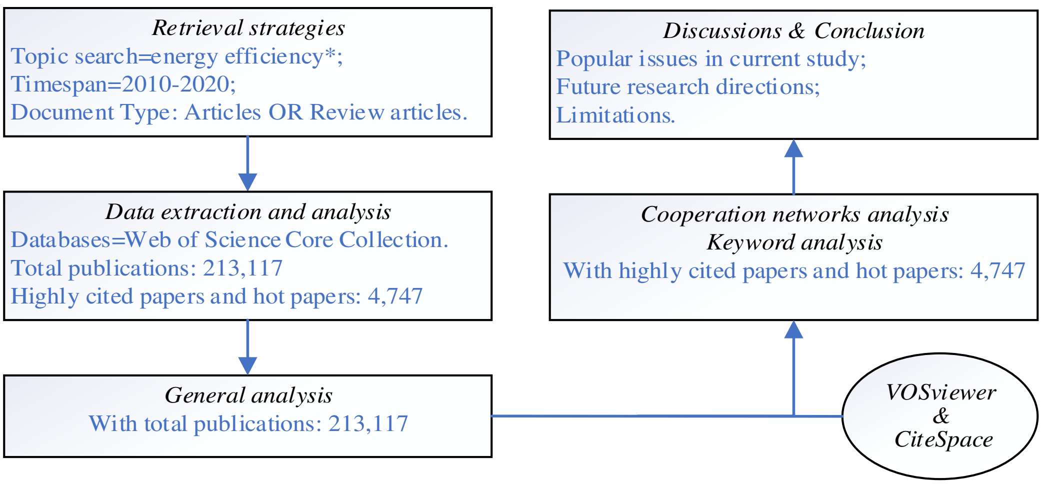

Fig. 1. Methodology framework of this paper

Results and Analysis

Results of the bibliometric analysis are presented in this section, including general analysis, cooperation network analysis, and keyword analysis. The general analysis presents the development and distribution of publications in the field of energy efficiency from the annual indicators, types, and source journals of the publications. Collaboration networks analysis utilized VOSviewer to clearly show the number of co-authored publications and collaborative relationships between different countries/ regions, institutions, or authors. It is an important way to quickly understand the frontiers in one field (Ji et al., 2021). Keywords can concisely express the conceptual frame that authors draw for their work (Henry et al., 2021), so cluster analysis, timeline view analysis, and timezone view analysis can intuitively show current popular issues and the dynamic development trend of keywords in different time periods. Then, some discussions about the limitations of current research and future research directions of energy efficiency literature are given.

General analysis

Actually, the first publication was published in Science to explain the impact of cheap nitrate on economic life in 1914 (Strong, 1914). However, the development of energy efficiency and breakthroughs in the past ten years have been effective. Therefore, this paper only analyzes the literature during 2010-2020. The annual number of energy efficiency publications from 2010 to 2020 is illustrated in Table 1. Since 2016, the number of global-related publications has exceeded 20,000, and the number of papers has increased by an average of 2% each year then.

Tab. 1. Annual publications from 2010 to 2020

Publication Years	Record Count	% of 213,117
2020	36,317	17.04
2019	32,019	15.024
2018	26,901	12.623
2017	23,396	10.978
2016	20,289	9.52
2015	17,619	8.267
2014	15,186	7.126
2013	13,043	6.12
2012	11,024	5.173
2011	9,575	4.493
2010	7,747	3.635

Based on the analysis of the Web of Science, the top 10 research areas of the publications are as shown in Figure 2. Engineering is the most popular research area. The number of publications in engineering is 64,030 and the proportion is 30.05%. Next, literature is also widespread in Chemistry (23.38%), Energy Fuels (22.34%), Materials Science (19.63%), Physics (17.15%), Science Technology Other Topics (14.67%), Environmental Sciences Ecology (8.63%), Thermodynamics (6.14%), Computer Science (6.12%), and Telecommunications (5%). Obviously, energy efficiency is widely distributed and related publications promote the development of research areas both social sciences and natural sciences.

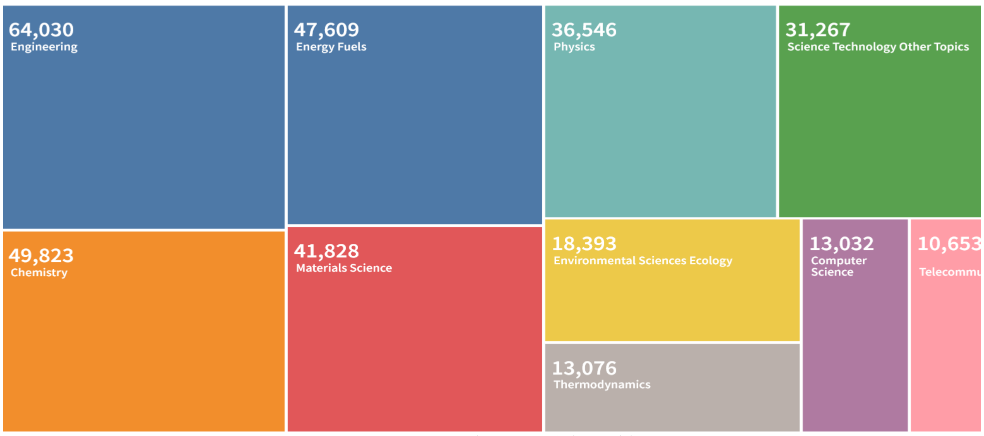

Fig. 2. Top 10 research areas of the publications

According to the statistics, energy efficiency literature comes from 181 countries/regions from 2010 to 2020. The map visualization of all countries/regions is shown in Figure 3. China (71,495 publications), the USA (35,477 publications), India (13,475 publications), South Korea (12,243 publications), Germany (10,736 publications), England (10,242 publications), Italy (8,670 publications), Japan (8,422 publications), Spain (7,445 publications) and Iran (7,400 publications) are the top 10 most productive countries/regions. Table 2 lists the top 10 most productive institutions and authors of the energy efficiency literature all over the world. As it should be, there are 5 and 7 from China respectively among the top 10 most productive affiliations and authors. This shows that the overall contribution of China to research on energy efficiency is relatively large.

Tab. 2. Top 10 most productive institutions & authors

Institutions	Record Count	Authors	Record Count
Chinese Academy of Sciences	11,291	Wang, Yang (CHINA)	1,612
United States Department of Energy Doe	4,637	Zhang, Yan (NORWAY)	1,479
Centre National De La Recherche Scientifique Cnrs	3,945	Li, Yu (USA)	1,322
University of California System	3,818	Liu, Yue (CHINA)	1,294
University of Chinese Academy of Sciences Cas	3,453	Zhang, Jie (CHINA)	1,230
Tsinghua University	3,288	Li, Jing (CHINA)	1,211
Indian Institute of Technology System Iit System	2,807	Wang, Lei (USA)	1,173
Helmholtz Association	2,068	Wang, Jun (CHINA)	1,141
Xi'an Jiaotong University	2,005	Zhang, Lin (CHINA)	1,087
Zhejiang University	1,962	Wang, Hui (CHINA)	974

Fig. 3. Map visualization of all countries/regions

Meanwhile, times cited can measure the quality and academic impact of publications. Citation analysis of journals is used to compare the relations of journals of energy efficiency literature. Most of these ten journals seem to be the most influential journals in the field of energy efficiency. The H-index is also introduced for evaluation. An index of H means that there are H papers that have each been cited at least H times. The academic influence of a journal is affected by many factors. The specific indicators are shown in Table 3. Total times cited in a journal are accounted for without self-citations. It is worth noting that the times cited in journals have little correlation with the number of publications but has a high correlation with the impact factor and H-index of a journal. The times cited of the most cited paper in *Journal of Materials Chemistry A*, which is with the highest impact factor, has reached 1020.

Tab. 3. Top 10 most influential journals with highly cited publications

Journal	Record Count	Impact Factor	Total Times Cited	H-index	The most cited paper	Times Cited
Energy	4,221	6.082	95,286	106	*(Pao & Tsai, 2011)*	412
International Journal of Hydrogen Energy	4,031	4.939	74,912	88	*(Ibrahim & Canan, 2015)*	735
Applied Energy	3,511	8.848	111,466	123	*(Tian & Zhao, 2013)*	816
Energies	3,291	2.702	20,819	48	*(Sun et al., 2017)*	136
Journal of Cleaner Production	3,108	7.246	64,363	88	*(Bocken et al., 2014)*	967
Energy Conversion and Management	2,679	8.208	62,689	91	*(Ayhan & Fatih Demirbas, 2011)*	532

ACS Applied Materials Interfaces	2,314	8.758	65,025	100	*(Zhang et al., 2010)*	436
Energy and Buildings	2,242	4.867	51,422	83	*(Oldewurtel et al., 2012)*	598
Applied Thermal Engineering	2,145	4.725	39,257	72	*(Charles & Christopher, 2013)*	277
Journal of Materials Chemistry A	2,131	11.301	71,446	108	*(Li et al., 2015)*	1020

Collaboration networks analysis

Collaboration networks can reflect the collaborative relationships among interconnected countries/regions/ institutions, references, and authors through coupling analysis and co-citation analysis. The principle of bibliographic coupling analysis is to measure the similarity of publications by the number of the same references cited in the publications (John, 1965). The principle of reference co-citation analysis is to measure the similarity between publications by the number of times two publications are cited together (Small, 1973). The based knowledge is composed of a collection of co-cited papers (reference co-citation analysis), and the research frontier is composed of a collection of citing papers that cite the based knowledge (bibliographic coupling analysis). For example, citing papers A and B in Figure 4 are related because they both cite C, D, E, and F. The cited papers M and N in Figure 5 are related because they are both cited by W, X, Y, and Z. Then, the citing papers A and B represent the research frontier, while the cited papers M and N are basic knowledge in the field.

The section analyzes co-country/region/institution networks, co-reference networks, and co-author networks by two methods of highly cited papers and hot papers in the energy efficiency field during 2010-2020. The size of the nodes in networks represents the number of publications.

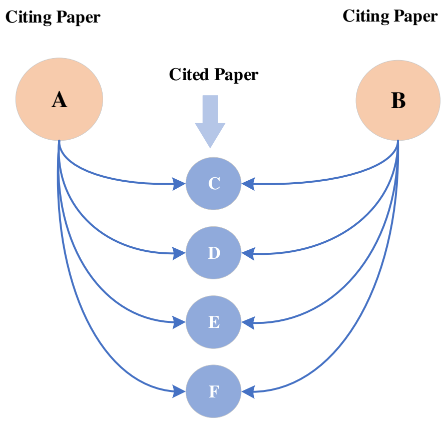

Fig. 4. Bibliographic coupling analysis

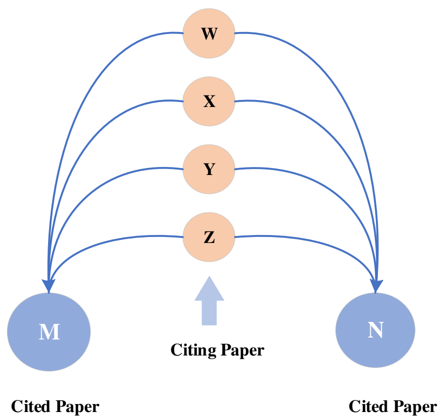

Fig. 5. Reference co-citation analysis

The co-country/region/institution networks

The co-country/region/institution collaboration network can be obtained by VOSviewer. Firstly, setting the minimum number of documents of a country to 5 and the minimum number of citations of a country to 0, the country/region collaboration network can be obtained and shown in Figure 6. Of 91 countries, 63 meet the threshold. Meanwhile, setting the minimum number of documents of an institution to 10 and the minimum number of citations of an institution to 5, the institution collaboration network can be obtained and shown in Figure 7. Of 3,138 institutions, 252 meet the threshold. Nodes connected by links indicate that there is a cooperative relationship between them. Different colored nodes in the figures represent different clusters. The number of published documents is one of the important indicators reflecting the importance of a certain research topic in a country/region/institution.

People's Republic of China (China) has the most cooperation with other countries/regions (2,169 times), and located the second and the third are the USA (1,468 times) and England (354 times), respectively. It can be seen from the different colored nodes in Figure 6 that these countries are divided into 6 clusters according to the coupling analysis. Among them, the cluster with the most publications is composed of China, the USA and Singapore. The red cluster in Figure 6 contains the most countries/regions, most of which are from South America and Africa. Belgium, Germany, Italy, Netherlands, Sweden, and Switzerland belong to a cluster, and England, France, Israel, Lebanon, and United Arab Emirates belong to another cluster. It is shown that the cooperation between countries/regions is geographically dispersed, and there is more cooperation between the same country/region or the same continent.

The Chinese Academy of Sciences publishes the most about energy efficiency in the world, with 407 publications and 114,112 citations. It is followed by Tsinghua University (155 publications and 36,011 citations) and Nanyang Technological University (81 publications and 15,539 citations). It can be seen from the different colored nodes in Figure 7 that these institutions are divided into 6 clusters according to the coupling analysis. To be specific, Stanford University, SLAC National Accelerator Laboratory (belonging to Stanford University), and the Zhejiang University of Technology form one of the clusters, indicating that the Zhejiang University of Technology has the closest connection with Stanford University in this field. The two clusters including the Chinese Academy of Sciences and Tsinghua University are almost all from China and the USA. There are also some institutions from Europe, which are dominated by The National Renewable Energy Laboratory (NREL), including the European Commission, Fraunhofer Institute for Solar Energy Systems (ISE), National Institute for Advanced Industrial Science and Technology, and The University of New South Wales, as a cluster. There are also some Asian institutions dominated by Nanyang Technological University as a cluster. Cross-regional cooperation between institutions related to energy efficiency literature needs to be further strengthened.

From the basic principle of bibliographic coupling analysis, two countries, China and the USA, and three institutions, the Chinese Academy of Sciences, Tsinghua University, and Nanyang Technological University, lead the research frontiers in this field.

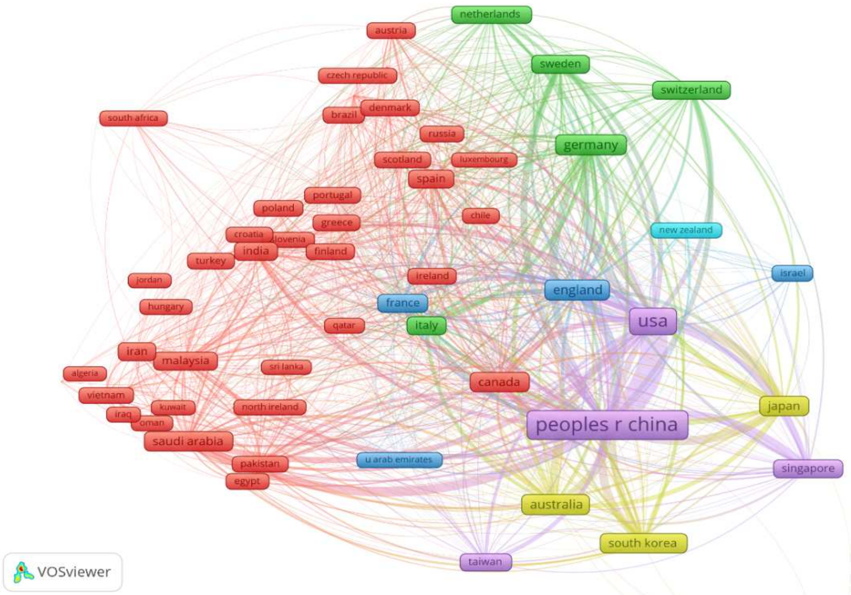

Fig. 6. Co-country/region network of the energy efficiency literature

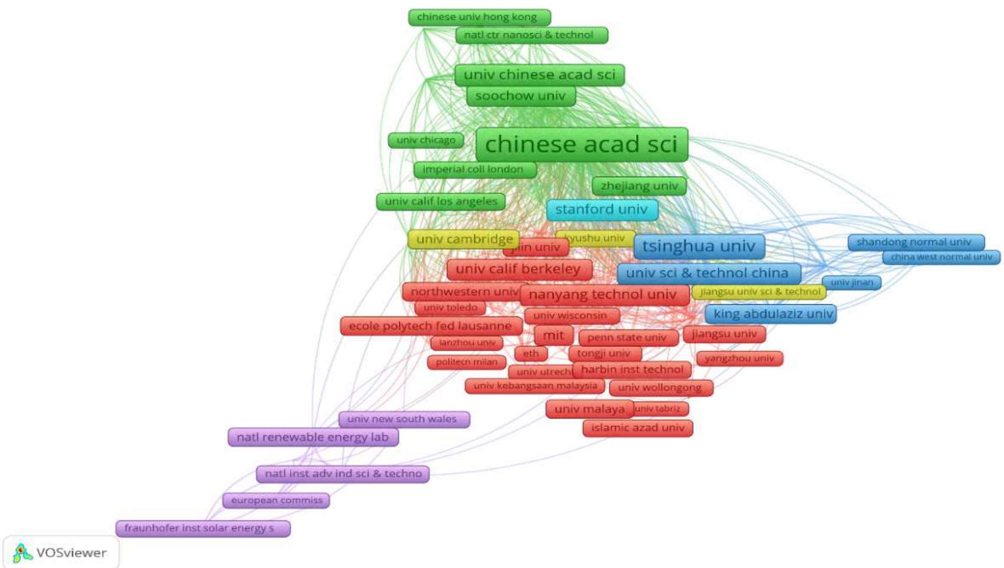

Fig. 7. Co-institution network of the energy efficiency literature

The co-reference networks

The citations reveal what scholars are interested in usually. The co-reference network is illustrated by co-citation analysis of cited references in the energy efficiency literature. We set the minimum number of citations of a cited reference as 50. Of the 270,601 cited references, 81 meet the threshold. For each of the 81 cited references, the total strength of the co-citation links with other cited references can be calculated. The total link strength of the node indicates the weight of citations of a reference. A total of 6 clusters are grouped; the co-reference networks are shown in Figure 8.

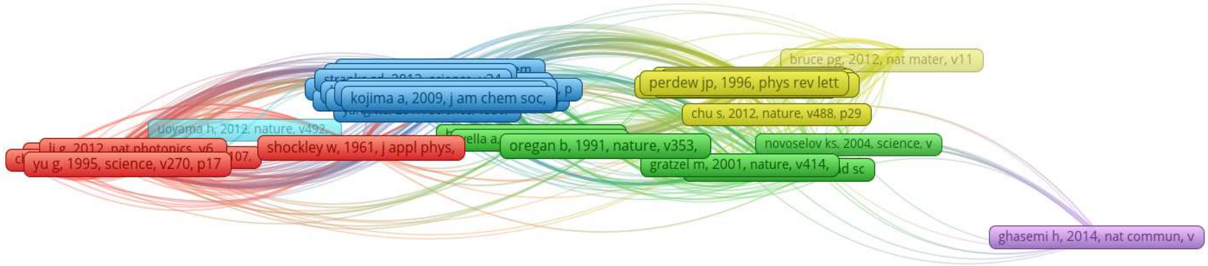

Fig. 8. Co-reference network of the energy efficiency literature

According to the principle of co-citation analysis, the cited references at the central node of each cluster are the representative references in one field. Table 4 lists the information of the top 6 classic literature related to energy efficiency. It can be found that these six classic publications are all from top journals in the field of energy efficiency research. Among them, there are articles published relatively recently, and some published relatively long ago. It shows that the energy efficiency literature often has significant innovative discoveries at a certain time interval.

Tab. 4. Top six classic literature related to energy efficiency

Cluster	Cited paper	Source	Type	Links	Citations
#1	*(Shockley & Queisser, 1961)*	*Journal of Applied Physics*	Article	65	119 508
#2	*(Fujishima & Honda, 1972)*	*Nature*	Article	48	161 553
#3	*(Kojima et al., 2009)*	*Journal of the American Chemical Society*	Article	52	155 1,123
#4	*(Perdew et al., 1996)*	*Physical Review Letters*	Article	53	172 589
#5	*(Ghasemi et al., 2014)*	*Nature Communications*	Article	23	74 267
#6	*(Uoyama et al., 2012)*	*Nature*	Article	22	61 58

The co-author networks

In order to analyze the current status of energy efficiency literature from a micro perspective, this paper explores the internal connections between researchers by the bibliographic coupling analysis and co-citation analysis, respectively. Firstly, this paper ignores publications with a large number of authors and sets the maximum number of authors per publication as 25. The minimum number of publications of an author is 10, and the minimum number of citations of an author is 5. Of the total of 19,498 authors, 110 meet the threshold, forming 4 clusters, as shown in the bibliographic coupling analysis on authors shown in Figure 9. The nodes represent different authors, and the weight of the node indicates how many publications there are. The lines represent the cooperative relationship between authors. Then, when conducting a co-citation analysis on cited authors, set the minimum number of citations of an author as 100. Of the 129,902 authors, 217 meet the threshold. A total of 6 clusters are grouped, as shown in Figure 10. The weight of the node indicates the citations of the author. The lines represent the cited relationship between authors.

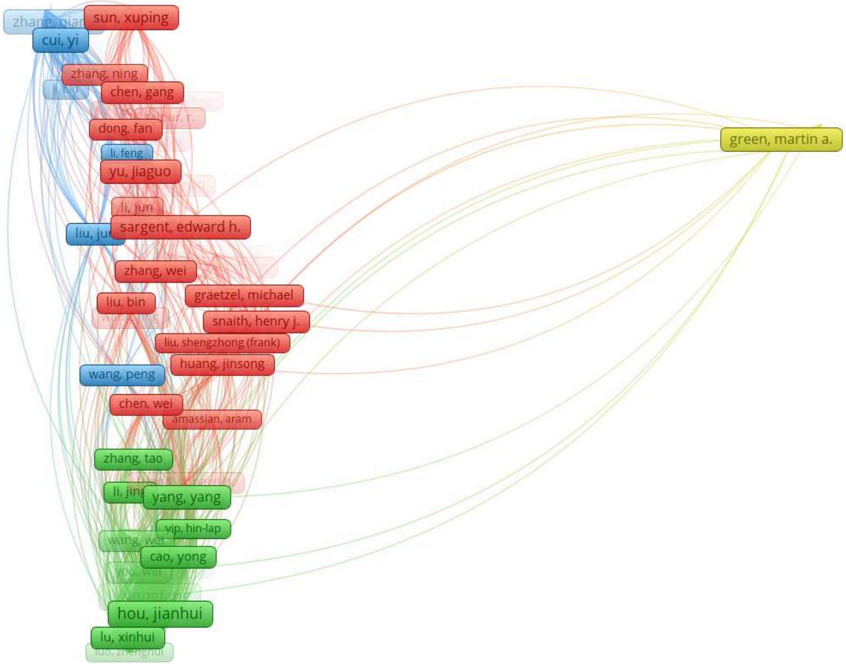

Fig. 9. Bibliographic coupling analysis of authors

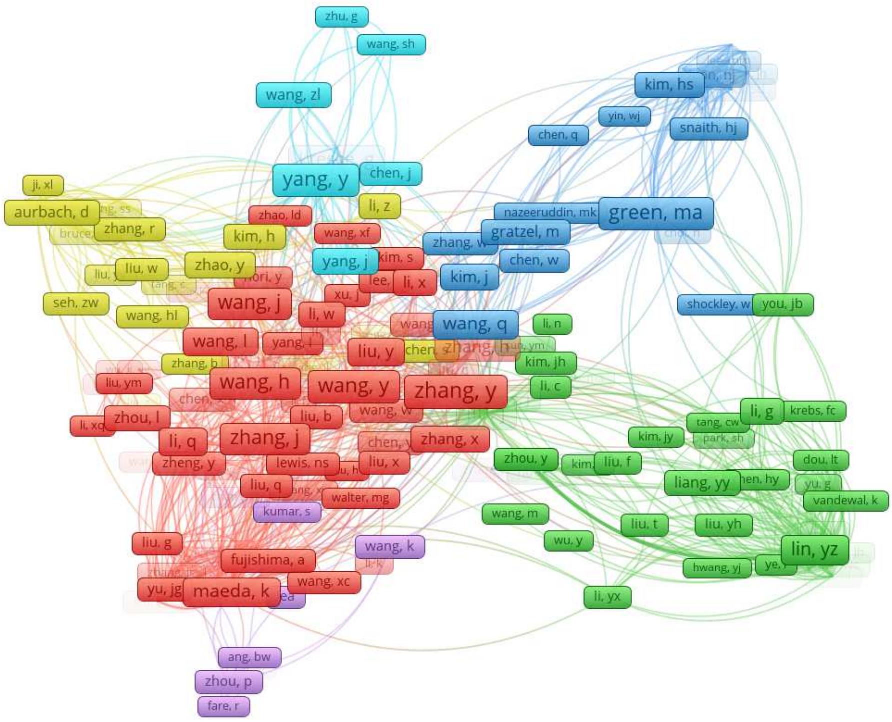

Fig. 10. Co-citation analysis of cited authors

Bibliographic coupling analysis on authors shows the cooperative relationship between authors with many publications, and the significant weight node (authors with more publications) holds the frontiers of research in the field of energy efficiency. Therefore, Li Yongfang (38 publications), Hou Jianhui (38 publications), Wang Zhonglin (34 publications), Cui Yi (34 publications), Sun Xuping (31 publications), and Zhang Qiang (31 publications) are the top 6 productive authors. Co-citation analysis on cited authors is an exploration of the mutual citation relationship among authors with more than 100 citations. The nodes with significant weight (authors with more citations) represent the theoretical basis of research in the field of energy efficiency. Therefore, Zhang Y (504 citations), Green Martin A (466 citations), Liu J (462 citations), Wang Y (462 citations), and Yang Y (446 citations) are the top 5 influential authors.

Keyword analysis

Keyword analysis visualization chart is more conducive to the analysis of research hotspots and the evolution of hotspots, especially with the use of burst term function (Liao et al., 2018). Generally, three ways of keyword visualization are cluster analysis, timeline view analysis, and time zone view analysis. The cluster analysis focuses on reflecting the structural features between clusters, highlighting key nodes and important links. The timeline view analysis focuses on delineating the relationship between clusters and the historical span of publications in a cluster. The time zone view analysis focuses on the view of the evolution of knowledge in the time dimension.

Cluster analysis

This paper starts with a co-occurrence analysis to reveal research hotspots first. The analysis of the co-occurrence of keywords is helpful in understanding the research direction and the central theme of the field. A total of 9,670 keywords provided by authors in the target literature are used, and the minimum number of occurrences of a single keyword is set to 5. There are 383 keywords that meet the threshold. The co-occurrence density visualization is shown in Figure 11. Then, we use CiteSpace to import the data and obtain a visual keyword cluster based on the generated information, and the clustering results are shown in Figure 12. The top six keywords with a high frequency (strong correlation) are energy efficiency (194 occurrences), photocatalysis (96 occurrences), energy storage (60 occurrences), solar energy (59 occurrences), renewable energy (58 occurrences), and energy consumption (49 occurrences). Co-occurrence analysis can reveal the internal correlation and microstructure. It shows that the energy efficiency literature mainly studies the improvement of energy efficiency in the consumption and storage of some renewable energy sources such as solar energy, etc.

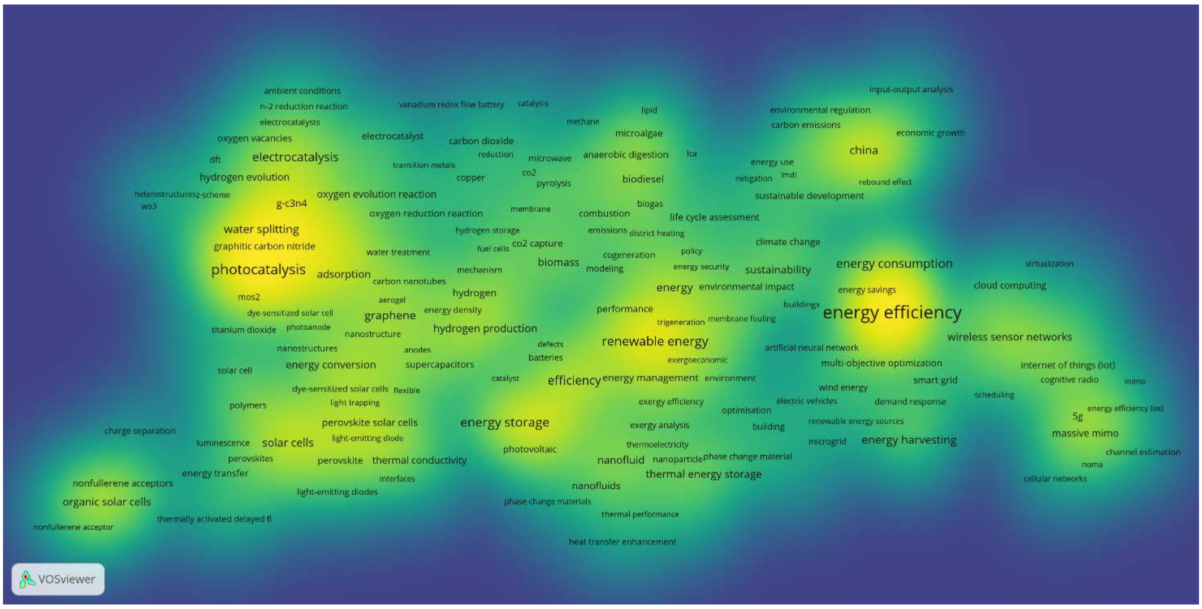

Fig. 11. Keyword co-occurrence of energy efficiency literature

All author keywords of selected energy efficiency literature are divided into 10 clusters, namely "energy consumption", "photocatalysis", "energy", "organic solar cells", "desalination", "energy harvesting", "energy storage", "Organic Rankine Cycle", "photosystem II" and "CO_2 fixation", and are shown in Figure 12. It reflects that they are the main research directions or topics to some extent. The color patches in keyword clustering in Figure 12 range from cool blue to warm red, indicating the change in time from early to recent. In addition, CiteSpace provides two indicators of Q value and S value according to the network structure and the clarity of clustering as the basis for the drawing effect of the visualization. The interval of Q value (Modularity) is [0,1), when the Q>0.3, it means that the divided community structure is significant. If the S value (weighted mean Silhouette)>0.5, it means that the clustering is generally considered reasonable (Chen, 2017; Chen et al., 2010). In the keyword clustering of energy efficiency literature, the value of Q is equal to 0.5714, and the value of S is equal to 0.8742. Therefore, the keyword clustering in this paper is reasonable and convincing. Finding special points and connecting lines are important for interpreting the network structure. Usually, the search for special points can be flexibly judged based on betweenness centrality and the burst of the results. In this paper, it is considered that author keywords with betweenness centrality greater than 0.1 are special points in the clustering results, which are listed in Table 5. These special points also show that the improvement of energy efficiency is for renewable energy. Renewable energy such as solar energy and biomass energy is of great significance to social and economic development.

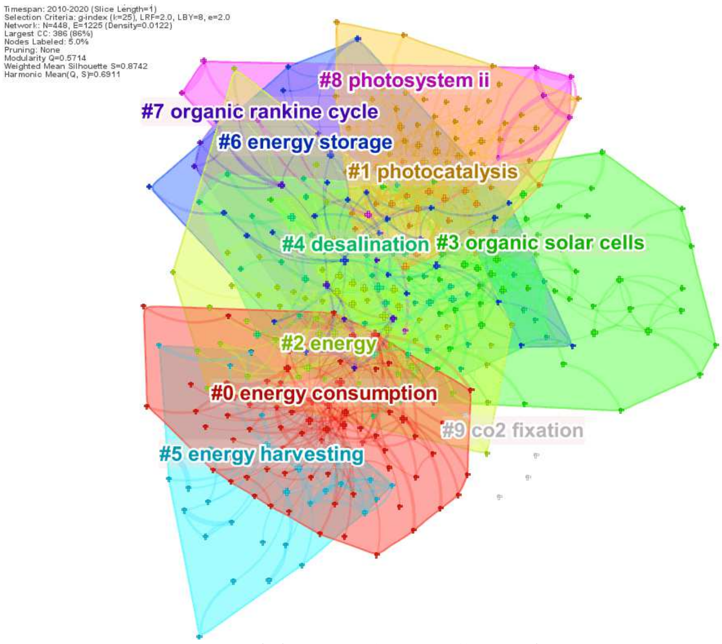

Fig. 12. Keyword clustering of energy efficiency literature

Tab. 5. The special points of the energy efficiency literature

Keywords	Record Count	Year of First Appearance	Centrality
energy efficiency	171	2010	0.29
renewable energy	52	2010	0.23
photocatalysis	96	2010	0.16
solar energy	53	2011	0.14
energy storage	54	2010	0.13
bioma	29	2010	0.13
energy	40	2010	0.12
efficiency	44	2011	0.11

Timeline view analysis

The timeline view analysis of energy efficiency in CiteSpace depicts ten clusters along with horizontal timelines, as shown in Figure 12. The timeline view analysis pays more attention to the internal connections and mutual influences between each cluster. All clusters are displayed from left to right and the keywords in each cluster are presented on the timeline when they first appeared. The legend of published time is shown on the top of the view and all clusters are arranged vertically in order of size from largest to smallest. The nodes on the same horizontal line show the historical publications of the corresponding cluster.

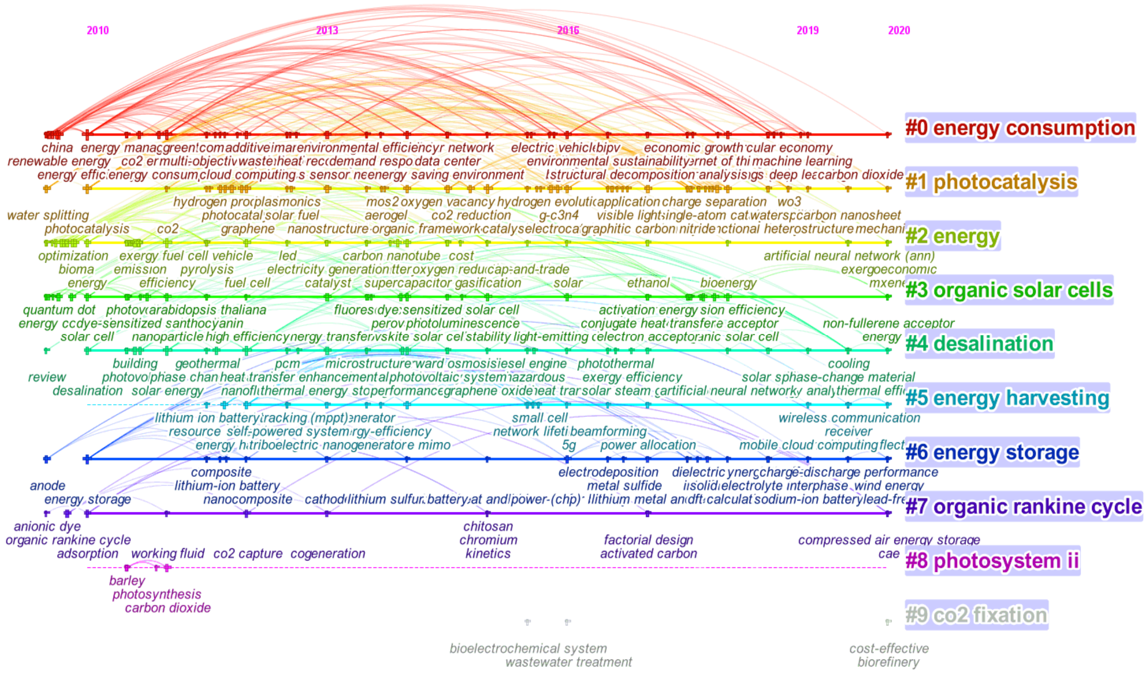

Fig. 13. A timeline view of energy efficiency literature

As can be seen from Figure 13, the first publications of clusters #0, #1, #2, #3, #4, #6, and #7 have all appeared since 2009 for the specific keyword clustering, while the first publication of the cluster #5 began to appear in 2012. From the node distribution, the literature production of clusters #0, #1, #2, #3, and #4 have developed steadily, with fruitful results during 2012-2013 and 2016-2018. The first publication of cluster #5 is from 2012; although it started late, the follow-up development is relatively rich. The development of clusters #6 and #7 is relatively stable. The first publication of cluster #8 began to appear in 2011, but the research is limited to this cluster. Within one year after it was proposed, there was almost no follow-up development from 2012 to 2020, and attention was reduced. The first publication of cluster #9 began to appear in 2015; there were also new iconic documents until 2019.

The burst term detection function in CiteSpace can be used to analyze research trends and frontier changes. The keywords with the citation bursts refer to a sudden increase in the number of citations for some keywords in a short period of time, which represents a new concept at a turning point in one certain year (Kenekayoro, 2020). Table 6 lists the top 20 keywords with the strongest citation bursts in the energy efficiency literature during 2020-2020. The blue lines in the table show the time interval of one year, and the red lines show the duration of keyword bursts.

The keywords "environment impact" and "Organic Rankine Cycle" were the earliest outbreaks with the highest burst strength with a value of 3.52, which were appeared in 2010 with "photovoltaic efficiency" and "life cycle assessment" and lasted for 4 years. Then, "energy conversion" had suddenly been on fire for two years. During 2011-2017, some of the keywords in chronological order were "dye-sensitized", "CO_2 emission", "optimization", and "resource allocation" became the burst keywords in this field. Although the duration of the burst keyword "CO_2 emission" is only 2 years, the intensity is 4.9, higher than other keywords in the same period. It indicates that the energy efficiency problem caused by environmental pollution has gradually attracted people's attention. With the change of time, the burst keywords in the energy efficiency literature changed to develop in the field of physical chemistry as follows: "perovskite", "light-emitting diode", "perovskite solar cell", "Oxygen vacancy", "CO_2 reduction", and "g-C_3N_4". "Oxygen vacancy" lasted the burst for 5 years in terms of duration. In recent years, some keywords like "organic solar cell", "non-fullerene acceptor", "power conversion efficiency", "electrocatalyst", and "density functional theory" have gradually become the frontier direction and the latest milestone of public research. In specific, the burst strength of the keyword "organic solar cell" was much higher than that of other keywords, with a value of 6.25. It can be shown that relevant studies on "organic solar cell" have made profound contributions to energy efficiency literature. The latest research topics are more detailed than earlier in the field of energy efficiency, including solar energy, CO_2 reduction, renewable energy, etc.

Tab. 6. The top 20 keywords with the strongest citation bursts from 2010 to 2020

Number	Keywords	Strength	Begin	End	2010-2020
1	environment impact	3.52	2010	2013	
2	Organic Rankine Cycle	3.52	2010	2013	
3	energy conversion	3.43	2010	2011	

4	photovoltaic efficiency	3.27	2010	2013
5	life cycle assessment	3.26	2010	2013
6	dye-sensitized	3.78	2011	2014
7	CO_2 emission	4.92	2012	2013
8	optimization	4.09	2014	2016
9	resource allocation	3.96	2016	2017
10	perovskite	3.94	2016	2018
11	light-emitting diode	3.53	2016	2018
12	perovskite solar cell	3.67	2017	2018
13	Oxygen vacancy	3.46	2017	2020
14	CO_2 reduction	3.32	2017	2018
15	g-C_3N_4	3.29	2017	2018
16	organic solar cell	6.25	2018	2020
17	non-fullerene acceptor	4.33	2018	2020
18	power conversion efficiency	4.05	2018	2020
19	electrocatalyst	3.75	2018	2020
20	density functional theory	3.51	2018	2020

Time zone view analysis

The time zone view analysis focuses on the view of the evolution of knowledge in the time dimension. Time zone view analysis can show the growth of energy efficiency literature in time. Each time zone in the view accommodates all the newly appeared keywords of the time period. A node represents a keyword and is in the year when it first appeared in the analyzed data set. The size of the nodes indicates the frequency of the keywords. The lines between nodes represent the temporal connection. If the keywords appear in the same paper together with the previous keywords, they will be connected by lines with the frequency of the previous period increasing by 1, and the size of the node becomes larger. The time zone view of energy efficiency literature is shown in Figure 14. It can be seen from the density of nodes in the time zone view that 2010-2013 was a booming period for the development of energy efficiency. After a year and a half of lows, publications in 2015 reached a peak, and then in the recent five years, the overall development of the publications tends to rise steadily.

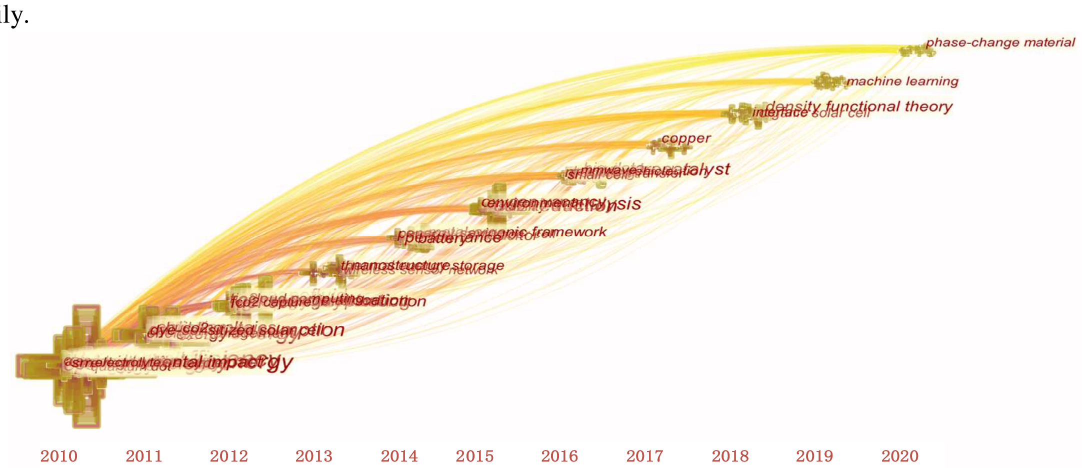

Fig. 14. Time zone view of energy efficiency literature

Discussion

Energy is an important factor in production. The increased input of energy factors in human production activities has greatly increased labor productivity and promoted economic and social development (Yu & He, 2020). However, over-reliance on non-renewable energy and excessive consumption of energy resources has become an important reason that affects the sustainable development of the economy and the deterioration of the ecological environment. Improving energy efficiency is an important way to solve energy conflicts. This paper provides a comprehensive view of energy efficiency trends worldwide through a bibliometric analysis of publications about energy efficiency. After exploring relevant literature, VOSviewer and CiteSpace are used to visualize. The number of publications has increased year by year. From the dimensions of countries/regions/ institutions, China and the Chinese have dominated the research on energy efficiency in recent years. On the one hand, due to the increasing energy demand, the contradiction between supply and demand is obvious in China. On the other hand, due to the large gap in energy efficiency between China and other countries. China has always maintained a situation of "high energy consumption and low output". Therefore, the potential for energy efficiency in China and how to improve energy efficiency still require in-depth research.

From the dimensions of references, authors, and keywords, this paper has explored the top-cited publications and highly cited authors. At the same time, highly productive countries/regions/ institutions and journals have been obtained. With the development of economics, more and more researches has shifted from the macro to the details. Generally speaking, more publications are focusing on renewable energy. From the results, the development of this field is relatively strong. The importance of energy efficiency as a policy goal is related to the interests of business, industrial competitiveness and energy security, and is increasingly related to environmental benefits such as the reduction of carbon dioxide emissions. Energy efficiency is an invisible resource (John, 2013). The ultimate goal of these documents in studying energy efficiency is to improve energy efficiency. It is regarded that improving energy efficiency is one of the important goals of current and future economic development in the world. Improving energy efficiency is also undoubtedly one of the ways to solve the accumulation of energy problems. In the future, it will of course be based on improving energy production efficiency and using clean energy technologies (Gvozdenac et al., 2019).

Through the results of the bibliometric analysis in this paper, taking the case of China with the largest amount of literature as an example, the following policy implications can be summarized:

(1) The government should optimize the industrial structure continuously and improve the traditional energy management models in the country. Simultaneously, speeding up the development of energy-efficient industries and encouraging the development of some low-energy-consumption industries should be followed up.

(2) The country needs to realize the recycling and comprehensive utilization of resources and promote the development of the circular economy. The utilization of resources involves many aspects. It is urgent to improve the efficiency of resource utilization in the production field and realize the recycling and comprehensive utilization of resources in various forms, which means we need to implement green production and green management.

(3) The country should invest more in scientific research so as to enhance the source of energy efficiency. The investment in scientific research should also be invested in high-tech industries in addition to the production of industrial equipment and energy-saving renovation in other industries.

(4) The government should gradually increase the proportion of renewable energy consumption and optimize energy efficiency through national tax incentives, government participation in investment, and equipment that encourages the use of new energy.

Energy efficiency issues still have more opportunities and challenges in the world. This paper has listed hot issues, research fronts, and explored future research trends, and also proposed some policy implications related to energy efficiency in response to current trends, as shown in Table 7.

Tab. 7. Challenge and policy implications for future research

Perspective	Points
Challenge	Imperfect energy management models
	The shortage of supply of energy
	Lack of a complete supporting legal system for circular economy and insufficient implementation efforts in the energy efficiency field
Policy Implications	Improve the traditional energy management model
	Achieve energy recycling
	Increase investment in scientific research and develop the study of renewable energy
	Adjust energy consumption structure

Conclusions

Firstly, this paper conducts a general analysis of the source, time, and authors of publications, and then extracts the 11-year highly cited papers from 2010 to 2020, and analyzes the relationship between the publication source, author, and institution through collaborative networks analysis. Finally, a detailed visual analysis of the keywords of these publications is carried out, and the visual graph obtained by the software is analyzed and discussed.

When trying to achieve intelligent use of energy and ensure that the same results are achieved with lower energy consumption, energy quality is a fundamental issue for all energy efficiency indicators. In this case, researchers need to explore the use of materials that actually use less energy or if certain materials are used to reduce energy consumption. In the final analysis, the problem of energy efficiency is widespread in the social economy, and energy quality indicators are used as macro indicators. It is necessary for researchers to study different methods to achieve maximum use efficiency under the premise of choosing effective energy materials, such as increasing the use efficiency of renewable energy in the case of expanding more renewable energy sources. It is also possible to use artificial intelligence theories to study some automation methods to monitor and optimize energy efficiency in real-time.

Some limitations in the research of energy efficiency need to be solved in the future. Many methods to improve energy efficiency include not only theoretically maximizing energy efficiency utilization but also need to propose policies and regulatory constraints to increase public awareness and change the behavior of energy system users. Encouragement funding for actions to improve energy efficiency has also been uneven so far. In addition, this paper uses a single database (WoSCC) to obtain the data used for bibliometric analysis. The bibliometric analysis in this paper is based on a large amount of energy efficiency literature; it reveals the overall situation in this field and provides some basic research directions but does not include a more detailed analysis of a specific direction of energy efficiency literature.

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