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Review

ENERGY EFFICIENCY AND COVID-19: A SYSTEMATIC LITERATURE REVIEW AND BIBLIOMETRIC ANALYSIS ON ECONOMIC EFFECTS

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Abstract. The Corona Virus Disease 2019 (COVID-19) epidemic has deferred global progress in energy efficiency to a decade-long low, posing a threat to the achievement of international climate goals, and also profoundly affected the development of economics. To gain insight into the research frontiers and hotspots in energy efficiency and COVID-19, a systematic literature review and bibliometric analysis on economic effects are performed with the help of the bibliometric tools VOSviewer and Bibliometrix. This paper selects all the publications retrieved based on the subject terms in the Web of Science core collection. Firstly, this article performs a performance analysis of related publications to present the development and distribution of energy efficiency and COVID-19 from research areas, relevant sources, and influential articles. Afterward, a visual analysis of the literature called science mapping analysis is implemented to display the structural and dynamic organization of knowledge in energy efficiency and COVID-19 research. In the end, detailed discussions of two research hotspots and some theoretical and practical implications are concluded in the systematic literature review and bibliometric analysis findings, which may contribute to further development for researchers in the field of energy efficiency and eventually propel the progress of society and economy in an all-round way.

Keywords: energy efficiency, COVID-19, science mapping, energy policies, energy consumption.

JEL Classification: C02, C40, C69, I18, L00.

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Introduction

Energy efficiency is high on the public policy agenda of most countries. The emphasis on energy efficiency as a policy goal is associated with increased commercial and industrial competitiveness, energy security benefits, and environmental benefits, such as reduced carbon emissions (Patterson, 1996). The sudden Corona Virus Disease 2019 (COVID-19) outbreak has far-reaching and widespread global economic, social and environmental impacts (Jiang et al., 2021; L. Y. Zhang et al., 2021). The energy industry is naturally not immune to (Mastropietro et al., 2020; Nicola et al., 2020). Energy efficiency has fallen victim to the COVID-19 pandemic.

The lockdown and recession are limiting efficiency gains and as companies reschedule investments in response to the economic crisis caused by COVID-19 in the future. Although, generally, whether COVID-19 brings enormous challenges or opportunities to the energy industry varies among scholars, it is still worthy of in-depth studies. Due to the influence of the spreading mechanism of the COVID-19 epidemic, a large number of cases spread rapidly among countries around the world. As a result, governments have introduced lockdown policies.

Reduced energy consumption in the industry and transport sector and increased consumption in the residential sector are the results of lockdown policies (Cortiços & Duarte, 2021). End-use energy efficiency is a notable sector that can help comprehend the depletion of energy resources and the deterioration of the environment during the COVID-19 epidemic. Primary sources of end-use energy efficiency include buildings, transportation, and industry. Buildings have the most effective energy use and greenhouse gas emissions globally. Lü et al. (2021) proposed using fluid dynamics models to explore indoor airborne transmission of coronaviruses to formulate healthy and energy-saving ventilation measures against Covid-19, thus improving building energy efficiency. The development of the transportation sector plays a vital role in stimulating the country's economic prosperity, and the industrial chain involved is closely related to the energy consumption (Wang et al., 2020a). In terms of carbon emissions, COVID-19 positively impacts transportation energy efficiency. However, COVID-19 has an unprecedented and extraordinary impact on the country from the perspective of activity volume, with a dramatic drop in the volume of all types of transportation Fields (Abu-Rayash & Dincer, 2020). Industries, directly and indirectly, contribute to about half of global carbon emissions, more than 80 percent of which come from the energy use (Worrell et al., 2008). COVID-19 has brought about an economic recession. The energy market is sluggish, and the cost of industrial production has been reduced. As a result, the energy transition accelerates, showing the characteristics of cleanliness, low carbonization, and digitalization. In particular, COVID-19 has brought uncertainty and turbulence to the energy system. Therefore, it is necessary to study the relationship to propose effective countermeasures to reduce energy efficiency in the emergence stage (Zhang et al., 2021).

Bibliometric analysis is mainly used to determine research trends after crawling many publications (Xu & Wang et al., 2021; Wang et al., 2020b). The bibliometric analysis presents a way to assess the development or characteristics of scholarship through a graphical representation. The graphs synthesize information from various aspects and show the results through horizontal and vertical coordinates, color, size, and labels. This paper uses a bibliometrix package based on R language and VOSviewer software to visualize. VOSviewer is suitable for performance analysis to analyze intercountry collaboration, the heat map of research distribution, and research hotspots through the keyword analysis (Li & Xu, 2021; Trianni et al., 2018). The bibliometrix package is employed for scientific mapping analysis, performing functions like those of VOSviewer. Bibliometric analysis is essentially a quantitative study style used to declare the qualitative characteristics of a particular field. The main strength of bibliometrics lies in transforming the quality of intangible scientific literature into manageable entities (Du et al., 2013). Studies involving multiple research areas have conducted a bibliometric analysis to discover the development of literature on the target topic, associated publication

sources, and collaboration network analysis between authors, journals, or regions (Xu & Ge et al., 2021). Several existing studies have investigated the effect of COVID-19 on energy efficiency. However, there are no papers that understand the relationship from the perspective of bibliometrics. This article provides a novel view, a systematic analysis, and an overview of the energy sector and society. The challenges and developments in energy efficiency under COVID-19 are also explored to derive an outlook for improving energy efficiency.

To gain insight into the research hotspots, frontiers, and technology trends in the field of energy efficiency and COVID-19, this article uses a systematic review of the literature and a bibliometric analysis to capture the basic features and dynamic changes of the relevant publications. Exactly, there are three main innovations in this paper:

(1) Identify the spatial and temporal distribution of energy efficiency and the COVID-19 literature in terms of annual indicators, research areas, country distribution of publications, journals, and highly cited articles.

(2) Start the conceptual structure with co-occurrence analysis of keywords to reveal research hotspots and reveal the intellectual and social structure of energy efficiency and COVID-19 literature to visualize co-citation network and country collaboration map of publications and sources.

(3) Focus on the systematic review and analysis of the two research hotspots of COVID-19 and energy policies and energy consumption to grasp the trend in energy efficiency research.

The rest of the paper is constructed as follows: Section 1 describes the data sources and methods for bibliometric analysis. Section 2 presents the results of the bibliometric study, including the performance analysis of the number, references, and distribution of publications; research areas; most relevant sources, and influential papers. Meanwhile, the science maps in conceptual, intellectual, and social terms are demonstrated visually. Finally, some discussions, including limitations, future implications, and conclusions, are summarized in Sections 3 and Section Conclusion, respectively.

1. Methodology

The research of this article follows reliable data and scientific methods to a comprehensive review of relevant publications and forms a historical perspective of its evolution and development.

1.1. Data source

Since COVID-19 has appeared in recent years, this study does not set the period and only considers publications in the Web of Science core collection (WoSCC). The Web of Science is currently one of the most authoritative academic databases and could offer detailed information on relevant publications for the science mapping analysis (Qin et al., 2021). It has collected a large amount of complex scientific literature on a global scale, which can be exported in different forms for further analysis from 1990 to the present (Cortés-Sánchez, 2019).

In this paper, the retrieval function is as follows: Databases=Web of Science Core Collection; Topic search= ("energy efficiency*" OR "end-use energy") AND ("COVID-19" OR "coronavirus disease 2019" OR "novel coronavirus" OR "Sars-Cov-2"); Document type: "articles" OR "review" OR "early access", and obtained 139 publications as of August 31, 2021, including author names, titles, abstracts, published dates, document types, addresses, and cited references. The unique character "*" is used at the end of the term to identify restrictions, thereby getting more accurate results. The detailed information of these publications is exported in plain text format and Tab-delimited (UTF-8) format for data analysis, synthesis, and interpretation. Retrieval strategies for energy efficiency and COVID-19 are shown in Table 1.

Table 1. Retrieval Strategies for Energy Efficiency and COVID-19

Retrieval type	Content
Database	Web of Science Core Collection
Topic research	(Energy efficiency*) AND ("COVID-19" OR "coronavirus disease 2019" OR "novel coronavirus" OR "Sars-Cov-2")
Document type	"articles" OR "review" OR "early access"
Language	English

1.2. A step-by-step research method

We adopt a step-by-step research method to understand the knowledge pattern in energy efficiency and the multi-level connection between energy efficiency and COVID-19. Firstly, this article uses bibliometric methodology to analyze related publications scientifically and quantitatively so that research ideas can be preliminarily formulated. Then, since this, a systematic literature review method describes the popular topics in energy efficiency to find potential research challenges. The framework of the step-by-step research method is depicted in Figure 1.

1.2.1. Bibliometric analysis

Bibliometrics can evaluate 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 (Garfield, 1979). It is also one of the appropriate methods to look into the field of energy efficiency field because it can reveal the evolution of various projects and measure internal relationships through the extensive intersection and combination of statistics, philology, and information science (Du et al., 2013; Yu & He, 2020). Furthermore, the ideas and theories of bibliometrics have gradually become a valuable way for many scholars to open up new academic research fields (Wang et al., 2021). Therefore, many advanced algorithms and sophisticated visual analysis tools have been developed to help scholars quickly perform bibliometric analysis.

In this paper, two bibliometric tools Biblioshiny and VOSviewer, are visually analyzed. Bibliometrix is an open-source instrument based on R language that performs comprehensive scientific mapping work, supporting a recommended workflow for bibliometric analyzes.

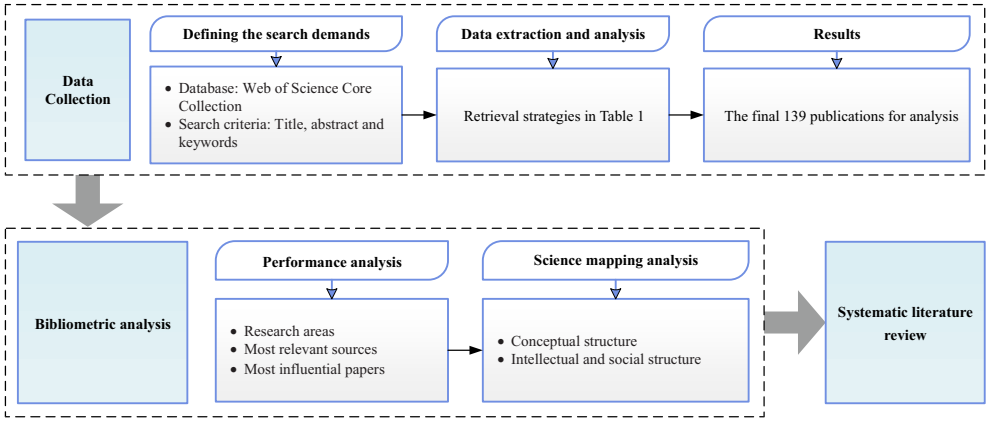

Figure 1. The framework of the step-by-step research method

Biblioshiny is developed based on Bibliometrix using the shiny software package of the R language. The difference is that the operating mode of Bibliometrix is to use text command lines. In contrast, Biblioshiny uses the shiny box to encapsulate the core code of Bibliometrix, creating a web-based data analysis framework. Therefore, users can perform related scientific measurement and visual analysis work on the interactive web interface, which significantly reduces the user's information input intensity and use threshold. At the same time, based on the feedback from related users and the latest research progress, Biblioshiny corrected the errors in some existing functional modules of Bibliometrix and added some new analysis functions. As a result, it is flexible and rapidly upgraded and integrated with other statistical R-packages (Aria & Cuccurullo, 2017). Using this tool, we have completed most of the bibliometric part of this article, that is, the performance analysis and scientific mapping analysis of the collected publications to present the research status and development trend of the energy efficiency and COVID-19 literature. In parallel, VOSviewer is a tool used to build and visualize bibliometric networks based on the Java environment (van Eck & Waltman, 2010). For example, it could build networks based on citations, bibliographic coupling, co-citation, or co-author relationships. With the assistance of two visual analytic approaches, this paper achieves an in-depth exploration of the intellectual structure of the core publications on energy efficiency and COVID-19.

1.2.2. Literature review

Bibliometric analysis can provide an objective understanding of the internal structure and overall external performance of the energy efficiency and COVID-19 field. The use of models or algorithms for statistics and visualization is relatively broad. Although the relationship between different attributes can be shown more clearly, the analysis results obtained are not deep enough. Therefore, qualitative research and manual literature review are carried out based on the clusters of the bibliometric analysis network of relevant publications to summarize the hot spots, status quo, and prospects of different research directions in the current

field to solve specific research problems in a targeted manner. The traditional qualitative literature review process may have the subjectivity of the evaluator. Combining it with the bibliometric analysis can exert its more significant potential. In this paper, these two methods complement each other to analyze the development of the energy efficiency and COVID-19 field more comprehensively.

2. Results of bibliometric analysis

Results of the bibliometric study are presented in this section, including performance analysis and science mapping analysis. Performance analysis shows the development and distribution of energy efficiency and COVID-19 from research areas, relevant sources, and influential papers. Science mapping analysis aims to display the structural and dynamic organization of knowledge in scientific research, enabling us to decipher the evolutionary nuances (Chen, 2017). It is an intuitive way to quickly understand the frontiers in one field.

2.1. Performance analysis

The first relevant publication was published in the *Journal of Intelligent & Fuzzy Systems*, which studied to improve the energy absorption of the crashworthiness of the car structure under the influence of the COVID-19 epidemic (Liu et al., 2020). The appearance and development of the COVID-19 epidemic began only in 2020. There are not many source publications available for analysis, but they are highly representative. The number of global-related publications is 41 in 2020 is 41, and in 2021 it has reached 98, showing the upsurge of research of the energy efficiency and COVID-19 epidemic field.

Based on the analysis results from Web of Science, the top 10 research areas of the publications are as shown in Figure 2. Energy Fuels is the most popular research area. The number of publications in Energy Fuels is 37, 26.62%. Next, literature is also widespread in Engineering (25.18%), Environmental Sciences Ecology (23.74%), Science Technology Other Topics (19.42%), Chemistry (18.39%), Biochemistry Molecular Biology (8.63%), Computer Science (6.48%), Physics (5.04%), Construction Building Technology (4.32%), and Materials Science (4.32%). The impact of the COVID-19 on energy efficiency covers a wide range of fields and promotes the development of research areas, both social sciences and natural sciences.

According to the statistics, the relevant energy efficiency and COVID-19 literature come from 55 countries/regions. The map visualization of all countries/regions is shown in Figure 3 below. The size of the blue circles in the figure represents the number of papers. China (35 publications) has made outstanding contributions to energy efficiency research as China attaches great importance to COVID-19 epidemic prevention. Subsequently, the USA (16 publications), India (15 publications), Spain (11 publications), Pakistan (10 publications), Australia (9 publications), England (9 publications), Germany (8 publications), Italy (8 publications) and Saudi Arabia (8 publications) constitute the top 10 most productive countries/regions.

Citation analysis of journals is used to compare the relations of journals of energy efficiency and COVID-19 literature. Meanwhile, times cited can measure the quality and academic

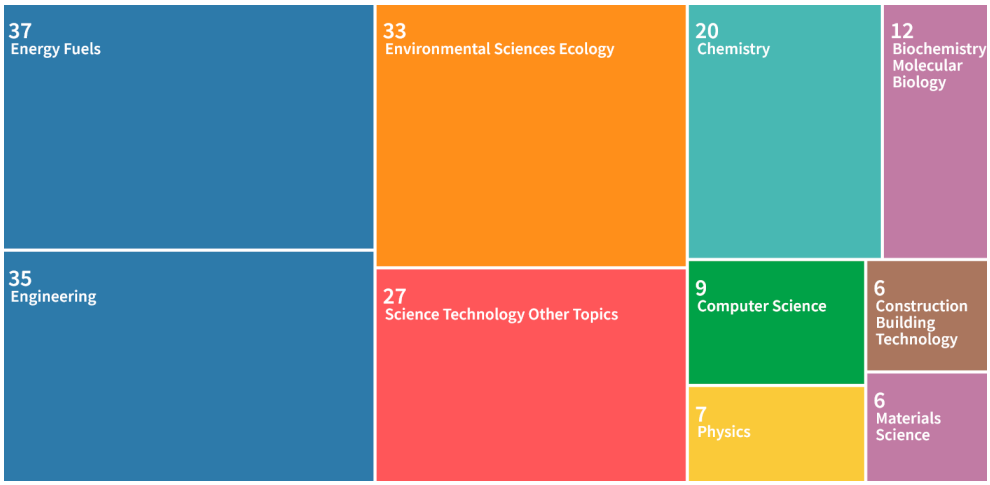

Figure 2. Top 10 research areas of the publications

Figure 3. Map visualization of all countries/regions

impact of publications. The academic influence of a journal is affected by many factors. Generally, most of these ten journals with a high H-index seem to be the most relevant sources or most influential journals. Overall, the 139 selected publications cover 85 different bases. We list the top 10 most relevant sources with cited energy efficiency indicators and the COVID-19 field in Table 2. Among them, the total number of citations of the journals does not include self-citations.

Table 2. Top 10 most relevant sources with highly cited publications

Journal	Record Count	Impact Factor	Total Times Cited
Energies	12	2.702	17
Sustainability	12	3.473	3
Applied Energy	6	8.848	45
Energy	4	6.082	49
Energy and Buildings	4	4.867	8
Environmental Science and Pollution Research	4	4.223	10
Renewable Sustainable Energy Reviews	4	14.982	12
IEEE Access	3	3.367	5
Journal of Biomolecular Structure & Dynamics	3	3.107	42
Sensors	3	3.576	1

Moreover, Figure 4 provides the year-wise growth and dynamics of the above top 10 relevant sources. It is easy to find that the top two sources come from *Energies* and *Sustainability*, with 12 publications updated to 2021. *Applied energy* owns the second rank with six publications, followed by *Energy* (4 publications). From source dynamics, all journals are distributed in a growing trend. The temporal evolution demonstrates that the trend in this field is positive.

Citations for a paper are generally regarded as appropriate for measuring its influence and authority (Yu et al., 2021). Figure 5 illustrates the top 20 most cited papers on global citations in energy efficiency and COVID-19 research. More than half of the publications have been cited more than ten times in total. Global citations are different from local ones but refer to the number of citations without filtering, which better characterizes one paper's scope of external influence. The publication by Nutho et al. (2020) published in *Biochemistry* has the most citations of the top 20 global cited publications, followed by Chang et al. (2020) and Klemeš et al. (2020).

Interestingly, the fourth-ranked paper titled "Impacts of COVID-19 on Energy Demand and Consumption: Challenges, Lessons and Emerging Opportunities" has 36 citations, despite being published as recently as 2021. This paper offered directions for new ways to increase energy efficiency and promote energy conservation after the COVID-19 pandemic (Jiang et al., 2021). Table 3 reports the specific total citations across the top 10 cited publications. The type of the ten publications all belongs to journal articles, which shows that relevant cutting-edge research is still active. For example, the sudden appearance of the novel coronavirus in 2019 has significantly impacted the life and health of people all over the world. Regarding research topics, energy efficiency in end-uses, such as in buildings, transportation, and industry after the COVID-19 pandemic, is increasingly playing an essential role (Zhang et al., 2021).

The total citations reveal what scholars are interested in usually. Nevertheless, the number of citations could not wholly determine the quality of a paper. Also, the other factors should be taken into account. The co-reference network is illustrated by co-citation analysis on the cited energy efficiency and COVID-19 literature references. We set the minimum number of citations of a cited reference as 5. Of the 8,852 cited references, 28 meet the threshold. For

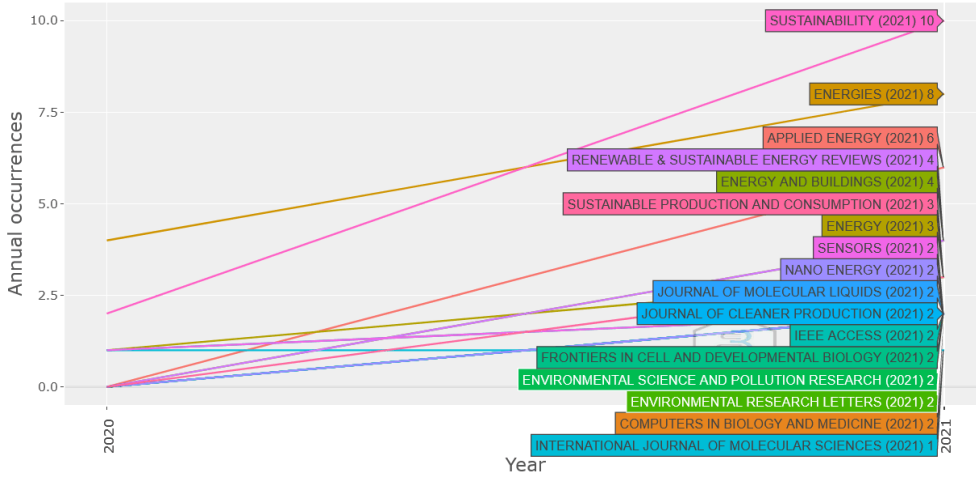

Figure 4. Source dynamics of top 10 most relevant journals

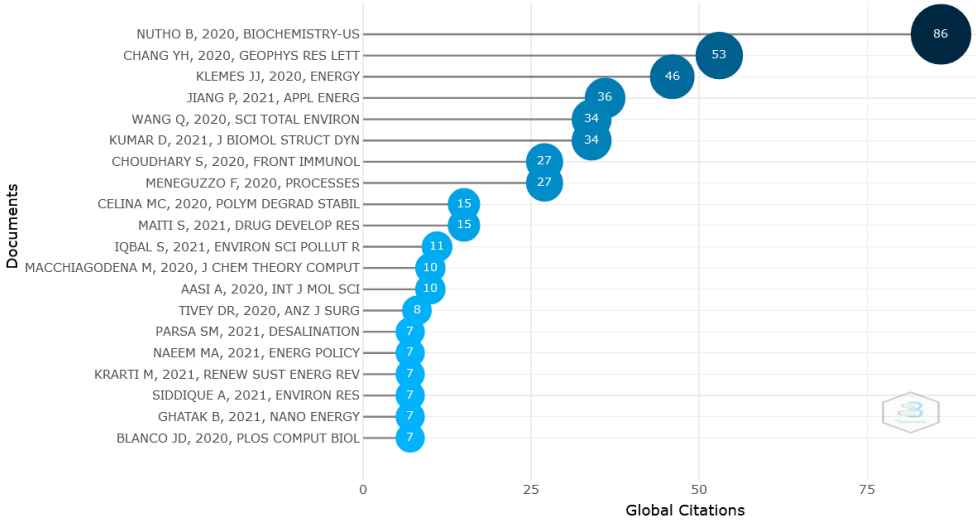

Figure 5. Top 20 global cited publications

each of the 28 cited references, the total strength of the co-citation links with other cited references can be calculated. The citations of the node indicate the weight of citations of a reference. A total of 4 clusters are grouped. The co-reference networks are shown in Figure 6.

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 4 classic references related to energy efficiency and COVID-19. These four classic publications are all published in 2020 and from leading journals in the field of energy efficiency. It shows that this field has had significant innovative discoveries recently.

Table 3. Top 10 most cited publications

NO.	Paper	DOI	Year	Total Citations
1	NUTHO B, 2020, BIOCHEMISTRY-US	10.1021/acs.biochem.0c00160	2020	86
2	CHANG YH, 2020, GEOPHYS RES LETT	10.1029/2020GL088533	2020	53
3	KLEMES JJ, 2020, ENERGY	10.1016/j.energy.2020.118701	2020	46
4	JIANG P, 2021, APPL ENERG	10.1016/j.apenergy.2021.116441	2021	36
5	WANG Q, 2020, SCI TOTAL ENVIRON	10.1016/j.scitotenv.2020.141158	2020	34
6	KUMAR D, 2021, J BIOMOL STRUCT DYN	10.1080/07391102.2020.1779131	2021	34
7	CHOUDHARY S, 2020, FRONT IMMUNOL	10.3389/fimmu.2020.01664	2020	27
8	MENEGUZZO F, 2020, PROCESSES	10.3390/pr8050549	2020	27
9	CELINA MC, 2020, POLYM DEGRAD STABIL	10.1016/j.polymdegradstab.2020.109251	2020	15
10	MAITI S, 2021, DRUG DEVELOP RES	10.1002/ddr.21730	2021	15

Table 4. Top 4 classic references related to energy efficiency and COVID-19

Cluster	Cited paper	Source	Type	Links	Citations
#1	(Lan et al., 2020)	Nature	Article	19	8
#2	(Jin et al., 2020)	Nature	Article	18	12
#3	(van Doremalen et al., 2020)	New England Journal of Medicine	Article	5	10
#4	(Le Quéré et al., 2020)	Nature Climate Change	Article	3	11

Figure 6. Co-reference network of the energy efficiency and COVID-19 literature

Authors are the main actors in the advancement of scientific research, and highly productive authors in a given field, in particular, are usually considered as critical players, controlling the evolutionary dynamics of future development. A total of 638 scholars have participated in the furtherance of energy efficiency and COVID-19 research from different countries. To some extent, information about the research institutions where the authors are located also implies whether a good research environment for researchers is good. The three-field plot with the fields of the most productive countries, authors, and affiliations from left to right is

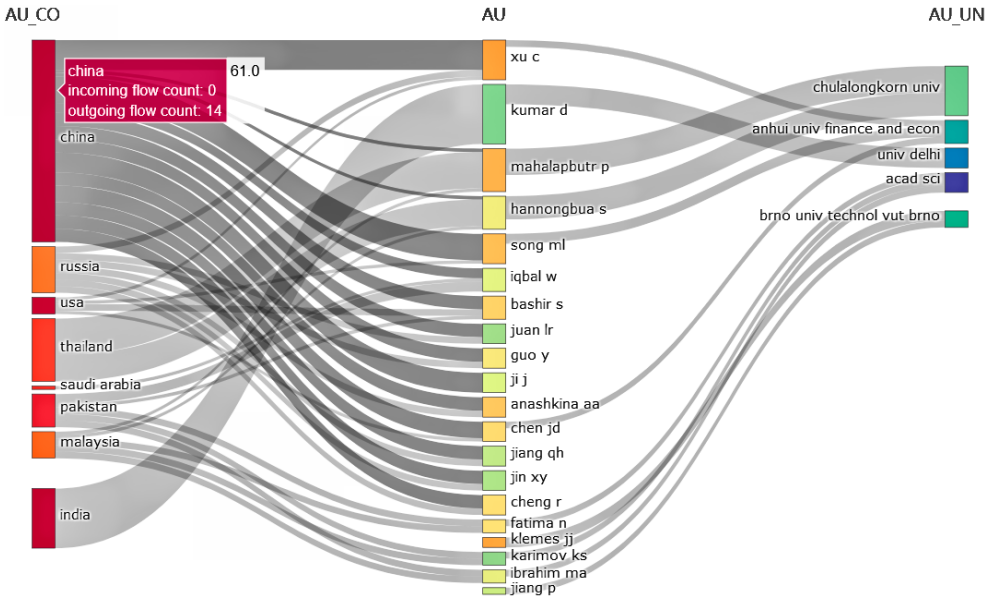

Figure 7. Three-field plot with the fields of the most productive countries, authors, and affiliations

shown in Figure 7. As it should be, there are 61 authors from China among the top productive affiliations and authors. This shows that the overall contribution of China to research on energy efficiency and COVID-19 is relatively significant.

2.2. Science mapping analysis

Concerning the analysis at the science mapping level, a series of bibliometric methods are exploited to identify the conceptual, intellectual, and social structures hidden in the energy efficiency and COVID-19 issues based on keywords.

2.2.1. Conceptual structure

This paper starts conceptual structure with co-occurrence analysis of keywords to reveal research hotspots. The analysis of the co-occurrence of keywords is based on counting. It is helpful to understand the research direction and the central theme of the field. Firstly, the keywords are examined by the word cloud shown in Figure 8. The word occurrences are measured by frequency. The word cloud analysis of keywords performs word frequency statistics on keywords in the relevant literature collection. By extracting keywords with higher occurrence frequency and highlighting them visually to form a keyword word cloud, readers can quickly appreciate the main elements of the text information. Keywords with high frequency, the larger the font in the figure.

Applying the co-occurrence analysis could detect associations between co-occurring feature items and reveal the corresponding mapping structure (Boyack & Klavans, 2010). Then, we load the Louvain cluster algorithm in the Biblioshiny, remove isolated nodes, and set the minimum number of edges is 2. The co-occurrence network generated by the 33 high-

frequency keywords plus is shown in Figure 9. 33 entries are divided into six clusters. Cluster 1 with eleven keywords (red bubbles), Cluster 2 with two keywords (blue bubbles), Cluster 3 with two keywords (green bubbles), Cluster 4 with nine keywords (purple bubbles), Cluster 5 with two keywords (orange bubbles), and seven keywords in Cluster 6 (brown bubbles).

Each cluster represents a different research topic to some extent. The betweenness and closeness for each node in the co-occurrence network are listed in Table 5, enabling us to measure the strength of a node's regulation and control capabilities in the network. Therefore, Cluster 1 is dominated by "energy", "efficiency", "performance", "impact" and "generation". Cluster 4 is controlled by "coronavirus", "optimization" and "Sars". Cluster 6 is mastered by "design", "carbon" and "identification". Cluster 2, Cluster 3, and Cluster 5 have only two keywords. Seeing that these clusters are related to biology, it is not the end-use energy efficiency discussed in this paper. Therefore, the values of betweenness are 0, and closeness values are much smaller than other clusters.

Figure 8. Word cloud of the keywords

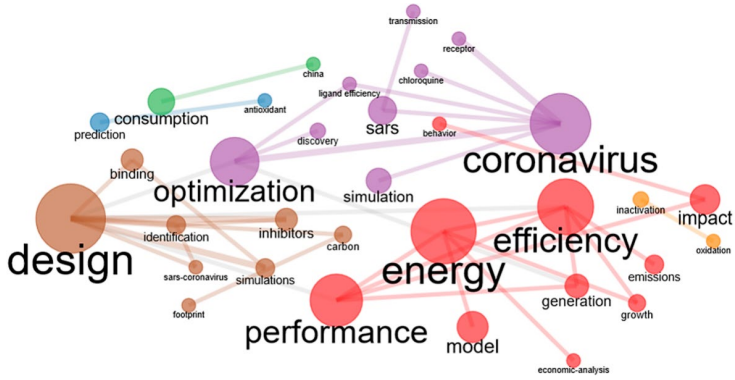

Figure 9. The betweenness for each node in the co-occurrence network

Table 5. The betweenness and closeness for each node in the co-occurrence network

No	Node	Cluster	Betweenness	Closeness
1	energy	1	50.50000000	0.003610108
2	efficiency	1	74.16666667	0.003846154
3	performance	1	77.66666667	0.003846154
4	impact	1	25.00000000	0.003533569
5	model	1	0.00000000	0.003311258
6	emissions	1	0.00000000	0.003508772
7	generation	1	40.50000000	0.003787879
8	behavior	1	0.00000000	0.003246753
9	economic-analysis	1	0.00000000	0.003311258
10	growth	1	0.00000000	0.003546099
11	prediction	2	0.00000000	0.000976563
12	antioxidant	2	0.00000000	0.000976563
13	consumption	3	0.00000000	0.000976563
14	China	3	0.00000000	0.000976563
15	coronavirus	4	114.00000000	0.003690037
16	optimization	4	153.66666670	0.003891051
17	Sars	4	25.00000000	0.003401361
18	simulation	4	0.00000000	0.003378378
19	receptor	4	0.00000000	0.003378378
20	transmission	4	0.00000000	0.003134796
21	chloroquine	4	0.00000000	0.003378378
22	discovery	4	0.00000000	0.003546099
23	ligand efficiency	4	0.00000000	0.003623188
24	inactivation	5	0.00000000	0.000976563
25	oxidation	5	0.00000000	0.000976563
26	design	6	190.10000000	0.004
27	binding	6	0.00000000	0.003649635
28	carbon	6	25.00000000	0.003663004
29	inhibitors	6	0.00000000	0.003649635
30	footprint	6	0.00000000	0.003355705
31	identification	6	0.40000000	0.003663004
32	Sars-Coronavirus	6	0.00000000	0.003649635
33	simulations	6	0.00000000	0.003649635

To measure the development of research topics and their mutual influence, the keywords associated with each cluster could be investigated via Bibliometrix. Then, four quadrants are divided into strategic diagrams of keywords plus energy efficiency and COVID-19 research (Figure 10). The abscissa represents centrality, and the ordinate represents density. The first quadrant (Motor themes) refers to essential research topics with well-developed momentum. It can be seen that the consumption of energy and carbon emissions are the current academic research craze. The research topics like decision-making in the second quadrant (Niche themes) belong to relatively niche research directions developed. The contents in the third quadrant (Emerging or disappearing themes) represent research directions that have emerged or are about to disappear. There is no good development either. For example, the current research on inactivation and oxidation is still in its infancy and is an emerging research hotspot. The research topics in the fourth quadrant (Basic themes) belong to the knowledge base of the research field. It is vital to the field, but it has not been well developed. Generally, some basic concepts like "energy efficiency" "carbon" may appear in this quadrant.

2.2.2. Intellectual and social structure

This section will further reveal the intellectual and social structures of the relevant literature. Specifically, we are committed to visualizing co-citation network and country collaboration map of publications and sources. The principle of reference co-citation analysis measures the similarity between publications by the number of times two publications are cited together (Small, 1973). The basic knowledge comprises a collection of co-cited papers by the co-citation analysis of references. Co-citation analysis also helps researchers understand the evolution of intelligence production status and research directions in specific areas. The top 50 papers in terms of total citations are selected for identifying categories by using the Louvain clustering algorithm. Louvain algorithm is a community discovery algorithm based on graph data, which is an implementation of optimizing the modularity of the relationship graph (Blondel et al., 2008). Figure 11 draws the co-citation network of cited energy efficiency and COVID-19 literature references. Each circle in Figure 11 represents a cited reference, and the volume of the circle is proportional to the number of citations of each reference. The lines between the circles indicate their co-citation relationship. In addition, colors can clearly distinguish the categories they belong to. Despite the wide range of categories, four clearly defined categories were observed. The blue cluster and red cluster contain many references and are closely related, indicating that references from these two clusters construct the basic knowledge of the field.

Co-citation analysis is also applied to the cited sources analysis, allowing us to capture the primary source in the field quickly. In the same way, the top 50 cited sources in terms of total citations are selected for identifying categories, the repulsion force is 0.1, and the minimum number of edges is 2. The edge-betweenness community detection algorithm generates ten clusters amongst the 50 most influential sources. Using the edge-betweenness community detection algorithm to process a directed graph does not try to maximize the modularity but only needs to find a directed path instead of an undirected path. When calculating the edge mid-degree scores, these scores are used to determine which edge to delete in the specific step (Newman & Girvan, 2004). Figure 12 shows the co-citation network of cited sources of energy efficiency and COVID-19 literature. Each square in Figure 12 represents a cited refer-

ence, and the volume of the square is proportional to the number of citations of each reference. The lines between the squares indicate their co-citation relationship. In addition, colors can clearly distinguish the categories they belong to. According to the statistics provided by the Biblioshiny in Bibliometrix, ten clusters with different colors can be obtained in Figure 12. Ten nodes with betweenness values above 15 are also identified, namely *Nature Communications*, *Nature*, *Science*, *ACS Nano*, *Journal of Hospital Infection*, *New England Journal of Medicine*, *Science of the Total Environment*, *Proceedings of the National Academy of Sciences of the United States of America*, *Journal of the American Medical Association*, and *The Lancet*. Due to the inclusion of the subject word COVID-19, the above journals have a lot of medical topics. In summary, this result highlights that these prestigious journals have become the primary source of references and occupy a dominant position in the co-citation network.

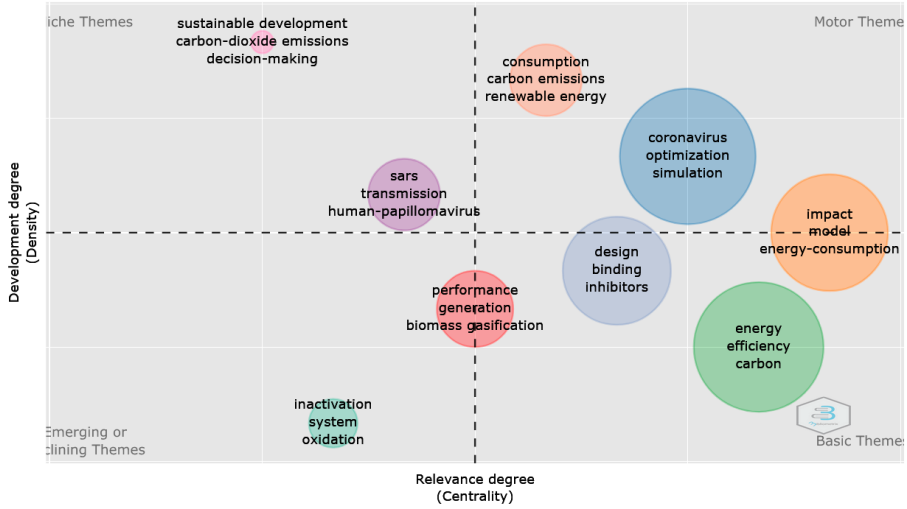

Figure 10. Strategic diagrams of keywords plus from energy efficiency and COVID-19 research

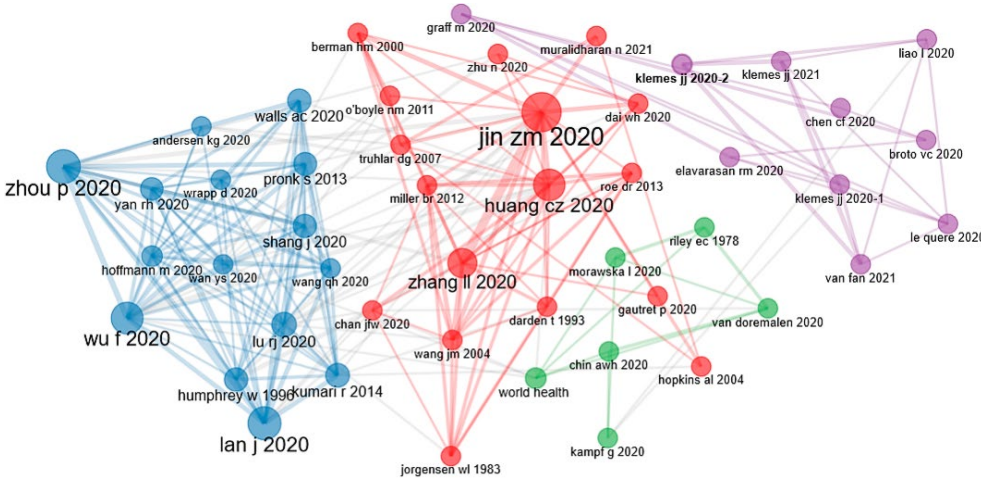

Figure 11. Co-citation network of cited references of the energy efficiency and COVID-19 literature

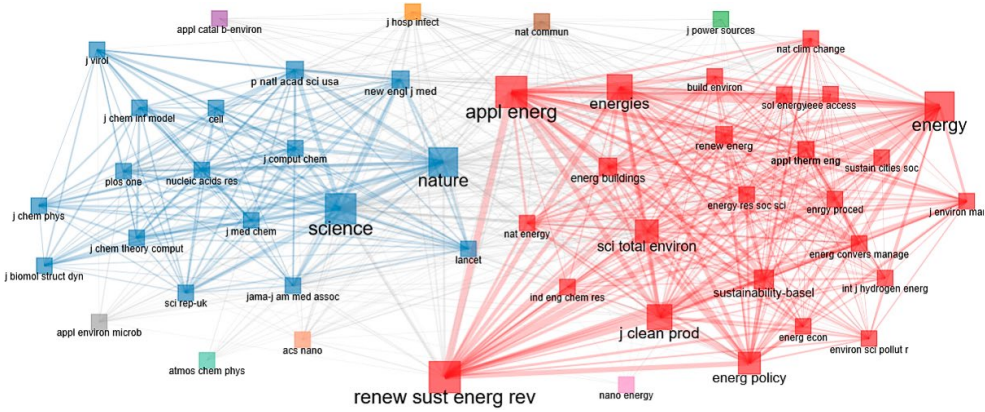

Figure 12. Co-citation network of cited sources of the energy efficiency and COVID-19 literature

The map visualization of all countries/regions is shown in Section 3.1. Considering the universality of cooperation and contacts between authors from different regions or countries, we have evaluated international cooperation. The number of minimum edges is set as 2. Collaboration world map of the energy efficiency and COVID-19 literature is visualized in Figure 13. The higher the productivity of a country or region, the darker its color, and the connection of pink lines indicates the presence of collaboration. The stronger the line, the higher the collaboration rate. According to statistics, 121 pairs of country/region key cooperation are on this map. Another prominent finding shows that scholars from the USA, the UK, and China are fostering the most robust collaborations, and they are building strong ties with their counterparts around the world, same for scholars from Pakistan and Saudi Arabia. They maintain the highest cooperation rate with a total of 4 co-authored publications. Since this field has just emerged, many authors from different countries or regions have not participated in the field of exchange and cooperation, and there is still much blank space waiting to be filled in the collaboration map.

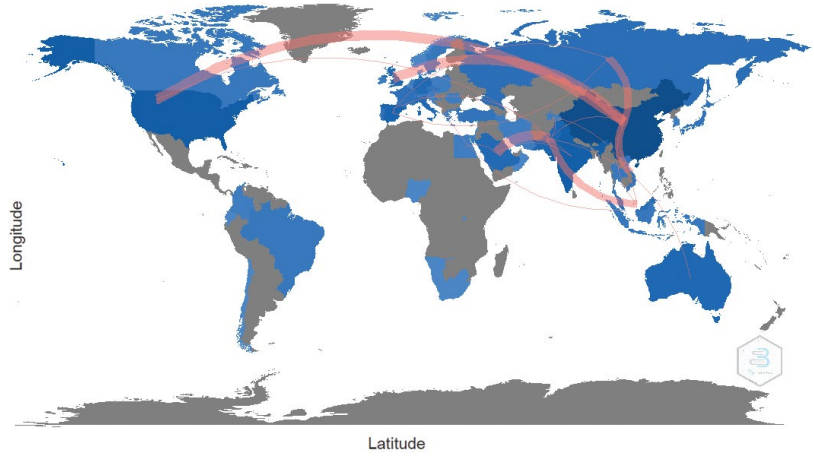

Figure 13. Collaboration world map of the energy efficiency and COVID-19 literature

3. Discussions

Bibliometric analysis by software is mainly based on the macro level. The growth mode of the national economy is often mainly dependent on production factors such as labor and resources, and to a large extent, it is at the expense of the environment, which will inevitably lead to serious damage to the ecological environment, low energy efficiency, especially the renewable energy (Yu & Luo, 2022). Nowadays, the slowdown in energy efficiency growth is mainly due to the impact of the COVID-19 epidemic, which has led to a downturn in the economic environment. The emergence of the COVID-19 is bound to bring about many new impacts. Industries such as construction, equipment, and automobiles have thus all been affected. After reading the literature and analyzing the results, we focus on the literature review and analysis of the two research hotspots of COVID-19 and energy policies and energy consumption in this section.

3.1. Energy policies and COVID-19

The COVID-19 pandemic has brought a cruel impact on countries around the world. The government's focus is on medical and health care directly. It also indirectly adopts emergency economic intervention measures to provide particular economic policy support for the people and factories. The pandemic will illuminate and compound existing crises in energy sovereignty (Brosemer et al., 2020). At this moment of crisis, the relevant energy sector has played a vital role equally. The government had formulated energy policies to provide energy guarantees, such as enabling the orderly conduct of medical treatments. The regular operation of hospitals and the delivery of anti-epidemic materials could be supported. It can also provide convenience for people during the lockdown.

Due to the intensification of the COVID-19, countries worldwide have begun to formulate more energy policies to slow down the environmental impact and shore up economic recovery. Policy-makers and researchers are highly concerned about relevant energy policies due to their wide-ranging impacts on society, the economy, and the environment. According to most of the objectives of energy policies in the existing literature, it can be summarized into policies aimed at economic issues and policies aimed at environmental issues, as shown in Figure 14. Methods and expected results of energy policies have also been illustrated. The COVID-19 pandemic is a global health crisis and an economic crisis. It also reveals and exacerbates existing environmental crises. Therefore, the current energy policies focus on economic and environmental issues. As the direct consequence of COVID-19, massive unemployment and self-employment bankruptcies have led to negative economic growth nationwide. At the same time, tax/pricing has not been lowered promptly, resulting in lower demand from the energy industry and delaying the complete rebound of global energy demand. Therefore, sustaining and creating employment is a significant priority for policy-makers and is indispensable for economic recovery (International Energy Agency [IEA], 2020). Therefore, the energy sector should effectively support an accelerated economic recovery and improve the economic level.

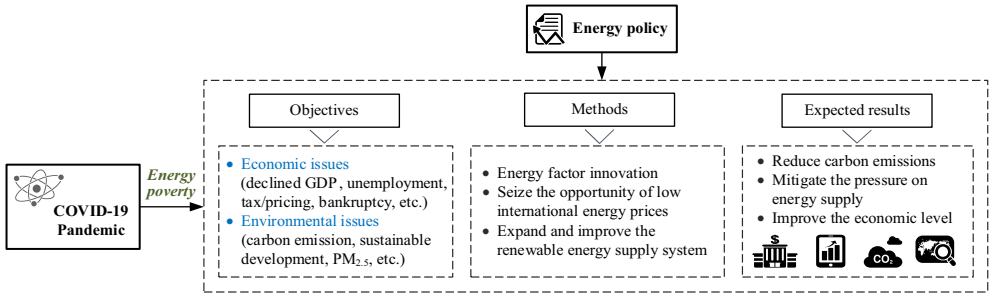

Figure 14. Energy policies and COVID-19

In order to achieve a sustainable optimization of the energy mix, many scholars have investigated varying energy policy frameworks under the COVID-19 pandemic. In Africa, COVID-19 had deeply damaged the ongoing social practices, innovations, and sustainable energy transitions (Sovacool et al., 2020). The sustainable energy transitions aim to ensure that no population is left behind as the globe decarbonizes. Efforts must be made to provide income support for workers throughout the transition, tailor local economic development policies for affected regions, and provide relevant training or retraining programs that lead to decent work. Then, the four main energy challenges for energy policies were proposed, including demand fluctuating and uncertainties, structure and pattern changes, associated environmental impacts, and the challenge to recover energy demand (Jiang et al., 2021). By analyzing the significant impacts of the COVID-19 pandemic on current and future sustainable energy policies in detail, we summarize the three main methods for improvement. Most of the relevant literature refers to innovation in energy factors while taking advantage of new opportunities for low international energy prices. On a broader level, policy-makers and the public will reflect on the impact of lockdowns on reduced traffic, pollution, and CO_2 emissions. At the same time, the government should expand and improve the energy supply system for renewable energy to achieve a balance between supply and demand, thus alleviating the dual pressures imposed by the environment and the economy. Energy subsidies can be executed to stimulate investment in energy-saving policies by declining the investment costs (Worrell et al., 2008). In other words, policy-makers must build resilience to energy poverty and respond to natural disasters to maintain energy equity. They are reducing reliance on non-renewable energy sources by improving energy efficiency. Therefore, in the context of the COVID-19 epidemic, countries must reduce their dependence on non-renewable energy sources by developing sensible energy policies to improve energy efficiency.

3.2. Energy consumption and COVID-19

Energy is a driving force for socio-economic development and a substance required for practical social activities. Since the COVID-19 epidemic, the international energy supply has been dramatically reduced, while international energy demand and consumption have experienced dramatic fluctuations. The impact of COVID-19 on the energy chain is also evident in energy supply, trade, consumption, and project investments, as most of the world's petrochemical-dependent energy groups and companies have suffered severe damage from the COVID-19

epidemic. Nevertheless, as the resource supply system is relatively well supported, the direct impact on the supply capacity is limited. At the same time, the COVID-19 epidemic has an illustrious pull-down effect on the demand for the varieties of energy, such as coal, oil, natural gas, and electricity, then on the supply. It is expected that the fundamentals of loose energy consumption and overall balance have not changed in the long term. It seems that the COVID-19 has a more significant impact on the short-term energy consumption demand, both on the supply side and the demand side.

From the point of view of the way of victimization, the COVID-19 epidemic has a brunt on end-use energy consumption intrinsically. The lockdown was adopted to reduce the COVID-19 epidemic situation had further increased the economic harm of COVID-19. Since then, the injure has expanded from end-use energy consumption to the entire upstream and downstream industrial chain and even caused a series of social problems, such as shortage of medical supplies, sluggish catering and tourism, blocked transportation, and rising unemployment. The specific consequences can be similarly summarized into economic and environmental aspects, as shown in Figure 15. The COVID-19 has had a long-tail effect on international oil demand, promoted the support of a green economy in various countries, and accelerated the electrification of automobiles (Anderson, 2004). Methods such as online offices and remote meetings have also changed people's work and life habits.

The relationship between energy consumption and COVID-19 is complex, and its performance varies across countries and even in various fields. In China, the energy consumption of industries and enterprises quickly made up after the impact of the COVID-19, but the energy consumption of commerce, building, and transportation took slightly longer to rebound, and the energy consumption of residents rose marginally. The lockdown policy caused by COVID-19 has also greatly affected the transportation industry in China (Zhang et al., 2021). Energy conservation and emission reduction have a long way to go, but on the other hand, it has promoted the development of vehicle electrification. In South Korea, building energy consumption is closely related to building types. The social alienation due to COVID-19 has changed energy consumption according to building use types, with energy consumption tending to decrease in most facilities and increase in residential facilities. Hence, the government requires the innovation of energy systems to effectively manage energy demand at the community level in the post-COVID-19 era (Kang et al., 2021). In India, energy consumption is strongly linked to the regional economy. The increasing number of COVID-19 cases at the beginning led to a sharp decline in energy consumption. Due to the long-term relationship between COVID-19 cases and energy consumption, in general, COVID-19 cases have had

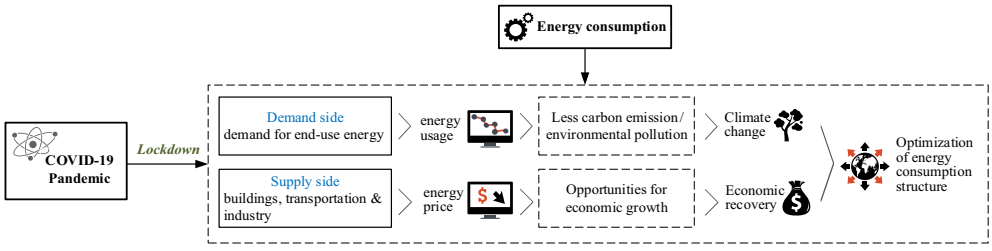

Figure 15. Energy consumption and COVID-19

positive impacts on energy consumption in India (Aruga et al., 2020). From a global perspective, the short-term energy consumption demand has dropped steeply, with little impact in the long term.

On the one hand, due to the reduction of world economic activities, the demand for input has been reduced. On the other hand, COVID-19 has prompted the petrochemical industry to suspend production and production, work and production, and the midstream and upstream raw materials could not be provided in time, which dealt a heavy blow to some processing and manufacturing industries. Countries should be brave enough to explore new models of digital energy economy and actively transform from original energy product suppliers to advanced energy technology creators or energy service providers. Global investment in energy efficiency had fallen by 12–15% in 2020 (IEA, 2020). Energy efficiency should be improved at all stages of the energy chain, from generation to end-use energy consumption.

3.3. Limitations and future implications

Despite the impact of the COVID-19 epidemic on energy efficiency, the demand for energy efficiency will increase in a complex overall economic state, and decarbonization in the energy structure will become increasingly important. In China, many energy sources, such as oil and gas, still rely on imports, and it is not yet possible to be entirely self-sufficient. In the face of various sudden safety accidents, it is difficult to respond in time. For example, at the time of the epidemic, the supply of power coal has tightened in the short term, the supply of electricity has tended to be flat, and oil and gas have indeed exceeded demand on the issue of energy supply. Although there is no impact on energy supply, the commissioning of renewable energy projects has also been lagging. The economy still holds vast potential in China. The slowdown in energy efficiency growth under the COVID-19 epidemic is expected but unworried. Every technology has a limited impact on productivity, valid for energy efficiency. As the room for improvement shrinks gradually, the closer the growth in energy efficiency is to the limit, the slower the growth rate. There is much more than countries could implement to reverse or prevent the decline in energy efficiency. For example, the energy sector invests in energy simultaneously through the digitalization of energy transformation, which is of practical significance to promote economic recovery, reduce carbon emissions, and keep sustainable and green (Beier et al., 2017).

Some policy implications are thus summarized to promote energy efficiency improvement and narrow the technological gap between countries/regions. After the epidemic, the economy has gradually entered a “new normal”, which depends on the low energy consumption, low emissions, and high-quality economic growth model in China (Ouyang et al., 2021). This requires the government to adopt supply-side reform policies, gradually eliminate outdated production capacity, and promote industrial transformation and upgrading to improve energy efficiency. Countries can also work to increase the energy output efficiency of internal combustion engine vehicles. Over the past few decades, internal combustion engine vehicles have significantly reduced oil demand due to increased energy efficiency. By strengthening public and private sector investment in buildings, transportation, and industry, further energy efficiency recovery efforts may be carried out on a global scale and can create more job opportunities globally. Furthermore, when China encounters obstacles to its energy transition,

we should improve the infrastructure of the national emergency storage management system and equipment, expand China's strategic oil and gas reserves, increase investment in capital construction projects for gas storage equipment. This can tighten the coordination of oil and gas trade and inventory adjustments and increase the efficiency of gas storage production and dispatch.

Meanwhile, we should pay attention to strengthening the ability to address external risks to oil and gas to ensure the response to energy problems in emergency and extreme situations. Finally, this section summarizes the energy efficiency and COVID-19 by reviewing the literature and then discusses the advantages, disadvantages, and outlook. However, it still does not allow for careful consideration of more details. Moreover, the relevant literature in this area is still small, and more in-depth and valuable studies will undoubtedly be available in the future.

Conclusions

Firstly, this article uses the VOSviewer bibliometric tool and the Bibliometrix package to perform the performance analysis and the scientific mapping analysis of publications to visualize the landscape and evolution of the literature on energy efficiency and COVID-19 on economic effects. After that, we capture two focus topics for the detailed discussion and analysis, namely "energy policies and COVID-19" and "energy consumption and COVID-19". Since the COVID-19 epidemic emerged in 2019, the research on energy efficiency has been relatively sparse but burgeoning. The most relevant publication sources are *Energies*, *Sustainability*, *Applied Energy*, *Energy*, and *Energy and Buildings*. In particular, *Energies* has accounted for most publications in this field in the past two years. In addition, four high-quality papers are also published in the top journal *Renewable Sustainable Energy Reviews*.

In general, countries worldwide have already engaged in some of the long-term challenges affecting energy efficiency, such as climate change, so coping with the short-term needs of the COVID-19 epidemic stimulus is still optimistic. In response to the specific status quo of each country, policy-makers are on board and ready to support the improvement of energy efficiency with unprecedented strength. At the same time, there are several limitations in energy efficiency research that need to be addressed in the future. Many approaches to improving energy efficiency include theoretical maximization of energy efficiency and the need to propose policies and regulatory constraints. For this cutting-edge research, we also need to investigate the relationship between energy efficiency and COVID-19 and the specific impact mechanisms and countermeasures to address. For energy efficiency, the opportunity has arrived, all the required drivers are in, the countries should not let it slip away.

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Author contributions

Xuan Yao, Zeshui Xu, Xinxin Wang, Lina Wang, Marinko Škare conceived the study and were responsible for the data collection, design and development of the data analysis as well as for data interpretation. Xuan Yao, Zeshui Xu, Xinxin Wang, Lina Wang wrote the first draft of the article.

Disclosure statement

Authors declare they do not have any competing financial, professional, or personal interests from other parties.

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