

Towards smart energy systems – A survey about the impact of COVID-19 pandemic on renewable energy research

Qiang Wang ^{a,b}, Rui Huang ^{a,b}, Rongrong Li ^{a,b,*}

^a School of Economics and Management, China University of Petroleum (East China), Qingdao, 266580, People's Republic of China

^b Institute for Energy Economics and Policy, China University of Petroleum (East China), Qingdao, 266580, People's Republic of China

ARTICLE INFO

Keywords:

COVID-19
Bibliometrics
Renewable energy
Visual analysis
Systematic literature review
Machine learning-based analysis (principle component analysis)

ABSTRACT

The COVID-19 pandemic has a significant impact on renewable energy. This work investigates the effect of pandemic on the renewable energy research from four aspects: the regional cooperation model of renewable energy research, the research hotspots of renewable energy during the pandemic, the development trend of renewable energy research hotspots in the post-pandemic, policy recommendations for development in the post-epidemic era. Systematic literature review (SLR), latent semantic analysis (LSA), and machine learning-based analysis (principle component analysis) are used to analyze the relevant literature on the COVID-19 and renewable energy in the Scopus database. The results of geographic visualization analysis show the COVID-19 pandemic has not hindered but promoted bilateral cooperation in the field of renewable energy among the "the Belt and Road" partner countries, with China at the core. The results of visual analysis of research hotspots show the research in the field of renewable energy during pandemics is divided into two categories: "opportunities" and "crisis", and further obtained five categories: sustainable development, environmental management, carbon emission, solar photovoltaic power, and wind power. The results of the keyword evolution map indicate the two main directions of renewable energy research in the post-pandemic: (1) Clean energy investment has become an important measure to revitalize the economy after the epidemic. (2) Energy efficiency research will effectively promote the sustainable development of renewable energy. Finally, we put forward policy suggestions on how to build a smart energy system in the post-epidemic era.

1. Introduction

On January 30, 2020, the World Health Organization recognized the COVID-19 outbreak as a Public Health Emergency of International Concern. The number of confirmed COVID-19 cases has exceeded 100 million, and the number of confirmed deaths has reached over 5 million by the end of January [1]. The outbreak of COVID-19 has affected health, society, and the economy and harmed the energy sector [2]. Table 1 shows the changes in the energy sector in various countries during the pandemic. Although not all regions face the same stringent restrictions, overall control measures have led to a 15% decline in China's weekly energy demand. Europe's weekly energy demand has fallen by 17%. According to the Global Energy Review 2020 released by the IEA [3], as of mid-April, the average weekly energy demand of countries in a state of complete lockdown worldwide has fallen by 25%, and countries in a state of partial lockdown have fallen by an average of 18% per week.

Although COVID-19 continues to affect the growth of the global energy industry, the renewable energy market, especially power generation technology, has shown its resilience to crises. Global Trends in Renewable Energy Investment 2020 released by the UN Environment Programme shows that COVID-19 has severely impacted the fossil fuel industry, while renewable energy is more cost-effective than ever. Countries should prioritize clean energy opportunities in economic recovery [6]. In the context of the decline in global energy demand, priority access to the grid and continuous installation of new power plants have made up for the decrease in industrial bioenergy and transportation biofuels. Therefore, the renewable energy used for power generation in 2020 increased by nearly 7% [7]. Renewable energy has increased substantially in the power generation mix. The share of renewable energy per hour has reached record levels in Belgium, Italy, Germany, Hungary, and the eastern United States. The consumption of renewable energy can promote sustainable economic growth, thereby improving the environment, enhancing the country's global image, and

* Corresponding author. School of Economics and Management, China University of Petroleum (East China), Qingdao, 266580, People's Republic of China.

E-mail addresses: wangqiang7@upc.edu.cn (Q. Wang), lirr@upc.edu.cn (R. Li).

Table 1

Impact of COVID-19 on global energy sector [4,5].

Country	Lockdown start	Lockdown end	Changes in energy demand
Australia	2020.3.23	2020.5.15	Weekday: 8%–10% decline in morning, 6%–8% decline in afternoon Weekend: 5%–6% decline in most of the day
China	2020.1.23	2020.4.8	8% decline in January and February (compared to the same time in 2019)
France	2020.3.17	2020.5.11	6%–12% decline in electricity demand
Germany	2020.3.20	2020.4.20	4%–6% decline in electricity demand
India	2020.3.25	2020.5.4	30% decline
Italy	2020.3.9	2020.5.4	10.1% decline in March

opening up international trade opportunities for environmentally friendly countries. Therefore, policies promoting renewable energy can bring about economic prosperity, create a better environment, and achieve critical sustainable development goals.

Changes in energy demand have also created a dilemma for the development of renewable energy. Overall, the start, construction and future investment of renewable energy projects are all facing obstacles. The COVID-19 outbreak has produced an interesting phenomenon in society as a whole: the epidemic has pushed society online. This sets the stage for the rapid expansion of digital tools for communication and organization, the digitization of smart energy systems and the widespread dissemination of smart energy technologies. Smart energy systems existed before the pandemic, but the COVID-19 outbreak has given new impetus to digitizing work and life [8]. First, individuals become more receptive and familiar with using digital technology. Second, the tools themselves have developed in the aforementioned areas. Both of these developments are driving the trend towards a fully digital and electrified age. In the process of using these new forms, people learn new ways of living and interacting. New attitudes and values, as well as behaviors and routines, have been formed, and none of these habits will be discarded when the virus threat subsides. These new attitudes and values could pave the way for wider use of renewable energy systems [9].

2. Literature review

Many scholars have discussed the impact of the COVID-19 epidemic on renewable energy development. Hosseini S.E. et al. studied how renewable energy can achieve sustainable development under the effect of the epidemic [10,11]. Akrofi M.M. et al. reviewed the African government's economic stimulus plan for the renewable energy sector during the epidemic and committed to promoting the country's transition to clean energy through the epidemic [12]. Naderipour A. et al. taking Malaysia as an example, showed the potential positive impact of COVID-19 on the environment to increase renewable energy generation [13]. Gosens J. expressed concerns about the Green New Deal through research on China [14]. Pamucar D. et al. used TODIM-D based fuzzy MCDM approach, provides a prioritization framework for the actions associated with zero-carbon city policies set out in London's strategy document [15]. Wan D. et al. proposed that after the COVID-19 epidemic, investors had greater investment enthusiasm for renewable energy companies than fossil energy companies [16]. Chiaramonti D. presented a meta-analysis of the relationship between the biofuel market and the achievement of decarbonization goals in the European transport market [17]. Research on renewable energy during the epidemic has involved various aspects such as finance, transportation, social welfare, etc. However, there is still a lack of assessment and resistance to the entire renewable energy system. Therefore, it is essential to understand and manage related documents in the energy field through high-quality shared data, obtain research hotspots, and predict future policies to reduce the impact of the energy field pandemic. The COVID-19 crisis disrupts the regular operation of the entire global statistics and data

system, causing the delay of planned censuses, surveys, and other data projects. The academic community urgently needs relevant institutions. Data innovation will help provide information for policy formulation in response to the crisis and accelerate the pace of recovery in the energy sector. To improve our understanding of renewable energy during the COVID-19 pandemic, we have adopted bibliometrics and systematic literature reviews for analysis in this field. Traditional reviews usually do not follow formal methods. Systematic reviews help reduce researchers' implicit bias [18]. Also, applying a straightforward review protocol and many documents increases the transparency of the review method and enables other researchers to reuse it in the future [19]. Therefore, the research motivation of this paper is:

- (i). Estimate the impact of the COVID-19 outbreak on the renewable energy sector.
- (ii). Explore the characteristics of regional cooperation in renewable energy research during the epidemic.
- (iii). Provide references for managers to formulate policies.

By discussing the opportunities and crisis encountered in the renewable energy field, the main contributions of this paper are:

- (i). Outline the changes in regional cooperation (especially the Belt and Road countries) and industry sectors (especially the power system) before and after the outbreak of COVID-19 from different perspectives.
- (ii). Summarize the research hotspots in the field of renewable energy in the post-epidemic era.
- (iii). Point out that smart energy system is the way to promote renewable energy sustainable development.

The innovation of this paper is to discuss some issues ignored by other papers, such as the similarities and differences in the research focus of renewable energy in different types of countries, finally conclude that smart energy systems can guide managers to make better decisions and promote the development of renewable energy.

The rest of the paper is as follows: Section 3 presents Materials and Methods, Section 4 is Results and analysis, and Section 5 is Conclusions.

3. Materials and Methods

In this article, we mainly use systematic literature review (SLR) and latent semantic analysis (LSA) for bibliometrics analysis, use unsupervised machine learning algorithm for principal component analysis and multiple regression analysis. Fig. 1 shows the specific process. Systematic literature review (SLR) provides a framework to integrate existing knowledge through a reproducible, scientific and transparent process. Compared with traditional narrative reviews, SLR can obtain a higher quality review process and results, reduce deviations and errors, and provide document mapping and data collection for specific research fields. Due to the reproducibility of the steps in the review process, it is more scientific and practical. LSA is a method that can abstract meaningful topic structures based on contextual similarity [20]. It is based on a singular value decomposition (SVD) algorithm applied to a document-by-document matrix of a corpus [21]. It can extract patterns of term occurrences in a corpus into an abstract, dense latent semantic dimension matrix, whose dimensionality is reduced to obtain similarity and knowledge representation [22]. Machine learning-based analysis (principal component analysis) is a multivariate statistical analysis method that uses the idea of dimensionality reduction to convert multiple indicators into a few irrelevant comprehensive indicators [23]. The main principle it adopts is to maximize the variance, not to change the data structure of the sample, to retain as much information as possible in the original variables, and to replace the original variables with as few principal components as possible, thereby simplifying the problem and enabling better analysis [24].

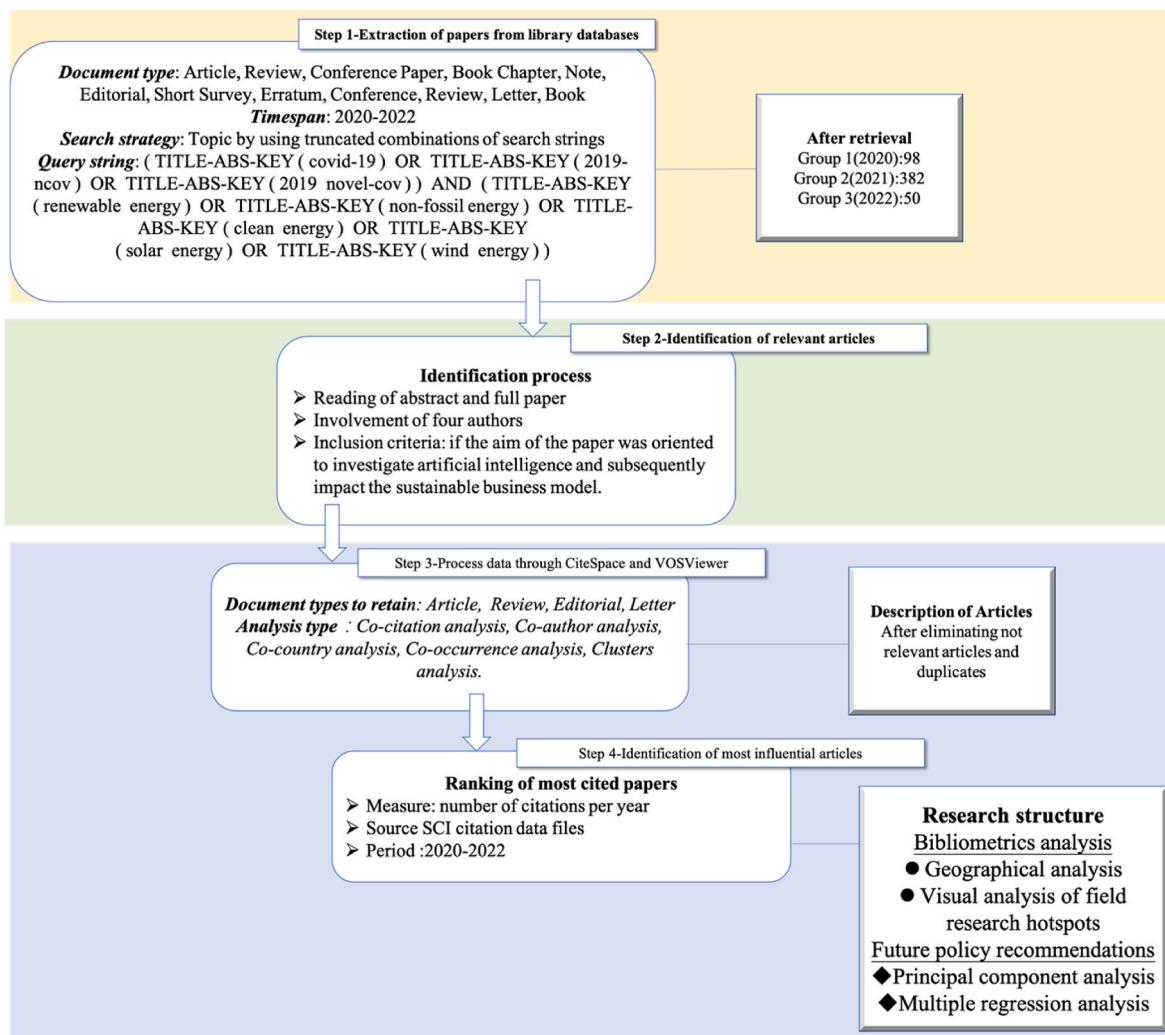


Fig. 1. The step of the document process through frame research.

When we use SLR, the first step we take is identification that in January 2022. This stage clarifies the research questions and research goals. When choosing data sources, we considered Google Scholar, ScienceDirect, Scopus, Web of Science, and SpringerLink. Google Scholar's preprint service has exploded in volume during the COVID-19 outbreak [25], which is critical for understanding and predicting epidemiological dynamics, implementing containment strategies, and effective diagnosis and treatment. But it also increases the risk of disclosing false information, as they are released without any independent quality control [26]. Scopus includes 19,000 source journals from 4000 publishers worldwide and is the world's largest database of abstracts and citations. Research has shown that Scopus is widely used when discussing scholarly publications during the COVID-19 outbreak [27]. Research published in peer-reviewed journals also has a good reputation and represents academic research in specific research fields. So we end up choosing the Scopus database. Finally, we use "(TITLE-ABS-KEY (covid-19) OR TITLE-ABS-KEY (2019-ncov) OR TITLE-ABS-KEY (2019 novel-cov)) AND (TITLE-ABS-KEY (renewable energy) OR TITLE-ABS-KEY (non-fossil energy) OR TITLE-ABS-KEY (clean energy) OR TITLE-ABS-KEY (solar energy) OR TITLE-ABS-KEY (wind energy))" as search in the Scopus database. As of January 2022, a total of 530 articles are obtained. The second step is to screen. This process determines the eligibility, inclusion, and exclusion criteria according to the established criteria, including or excluding articles. We select the articles published from January 2020 to 2022, including

systematic reviews or review papers, conference papers, conference proceedings, book chapters, series and books. The purpose is to fully reflect the research changes in renewable energy before and after the epidemic. The third step is the eligibility process. In this process, articles are manually screened according to established standards to remove repetitive or unrelated articles. The last step is data abstraction and analysis. The selected articles are evaluated, reviewed, and analyzed through CiteSpace, VOSViewer and Minitab. By reading the title, abstract and full text, the next stage we use LSA for topic analysis and bibliometrics for performance indicator analysis, uses Minitab for principal component analysis.

4. Results and analysis

4.1. Geographical analysis

4.1.1. Geographical distribution of publications

Different countries/regions have additional research capabilities, which will affect the geographic distribution of research work. Fig. 2 shows the global distribution of publications, with shades of color representing the number of publications by country or region. From the total number of intercontinental countries, there are fewer countries in Africa participating in the study. Other regions such as North America, Europe, East Asia, and Central Asia are relatively even. In terms of national development level, developed countries such as the United States,

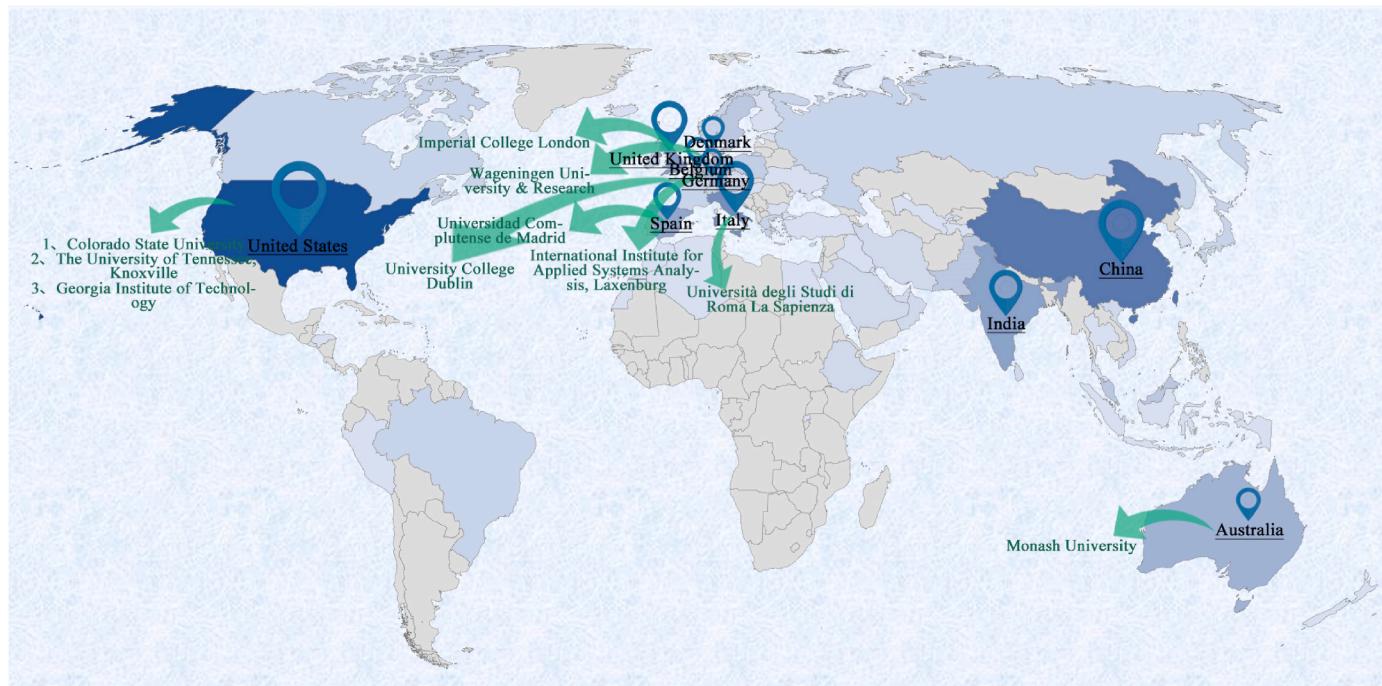


Fig. 2. Country coloring map by the number of publications.

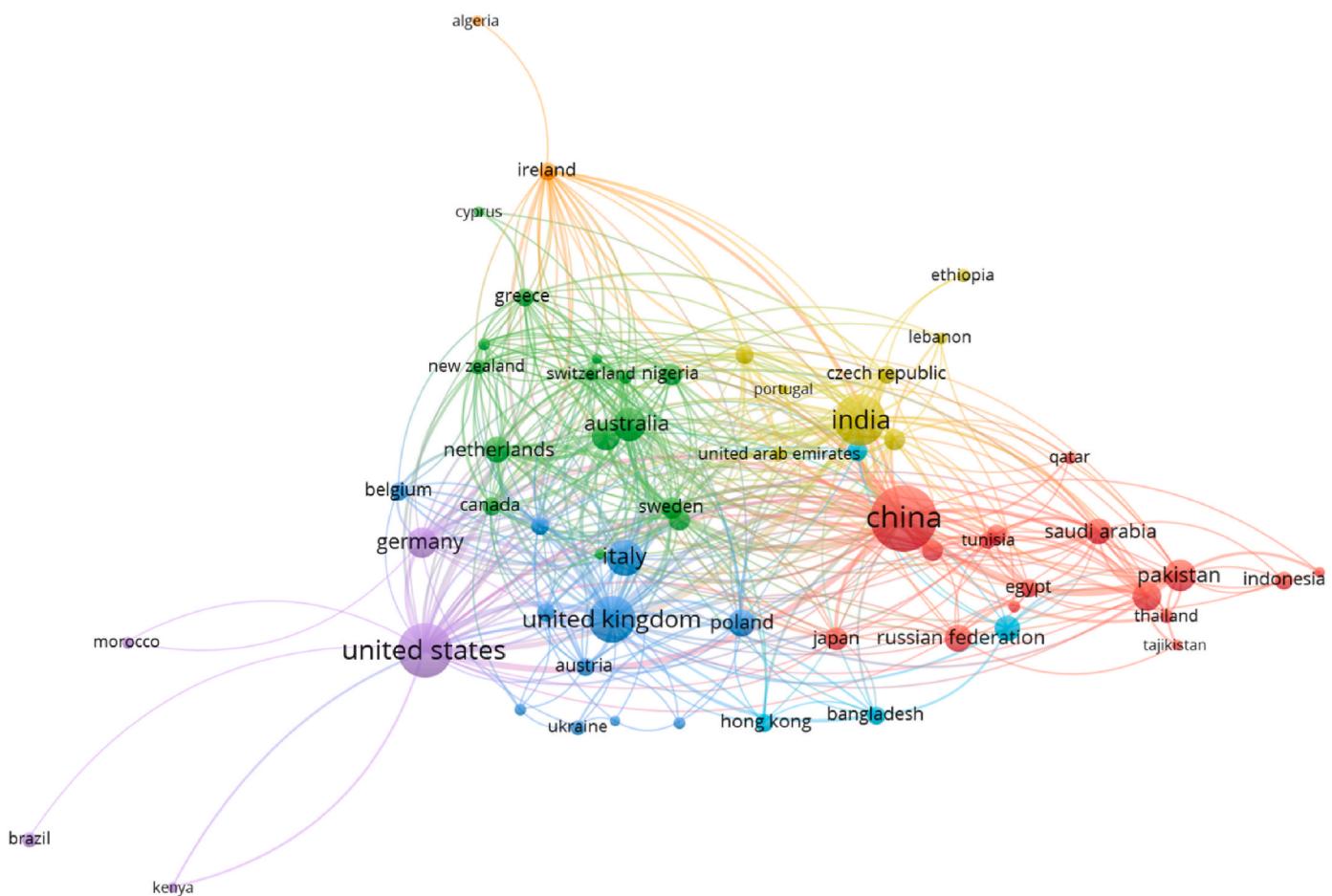


Fig. 3. The cooperation network of the country during COVID-19.

the United Kingdom, Italy, and Germany have more publications. Still, developing countries such as China and India have also shown interest in this field. We find a noteworthy phenomenon: Non-governmental and neutral international research organizations play an important role. Take the International Institute for Applied Systems Analysis as an example. This project covers more than 20 countries in Asia, Africa, America, and Europe.

4.1.2. Regional cooperation analysis

In Fig. 3 we find: the United States, China, the United Kingdom, and other countries still have a high volume and centrality of publications during the pandemic. It is worth noting that the map shows a research group centered on China, including Bulgaria, Saudi Arabia, Pakistan, and Malaysia. We find that these countries are all member states of the Chinese government to carry out the "the Belt and Road" initiative. In the first half of 2020, China's investment in renewable energy in countries along the "One Belt One Road" surpassed fossil energy for the first time, reaching 58.1%. This seems to reflect the new developments in multilateral and bilateral cooperation between governments and renewable energy investment during the pandemic.

4.2. Visual analysis of field research hotspots

4.2.1. Subject co-citation analysis

The cited documents in the original records constitute the knowledge base of the research field. The cluster analysis and evolution research of the knowledge are the basis for distinguishing the research frontiers in this field. This study uses the Scopus database's data to draw a visual map of the "renewable energy development during COVID-19" based on the document co-citation network. In the timeline view of Fig. 4, documents of the same cluster are placed on the same horizontal line. The time of the document is placed at the top of the view, and the time to the right is closer. In the timeline view, we can clearly get the number of documents in each cluster. The more documents in the cluster, the more important the obtained cluster field is. We mainly find eight main clusters in Fig. 4: #0 cov-2 pandemic, #1 resilient energy future, #2 hedging, #3 shift progress, #4 urban outdoor air pollution level, #5 clean energy firm, #6 energy sector, #7 power grid, #8 economic growth. Cited documents with high centrality no longer focus on the pathological research and social impact of early COVID-19, which seems

to reflect that research in the field of renewable energy has formed a relatively mature infrastructure system during the pandemic. We continue to analyze the cited documents with higher centrality among these eight categories, and find that the cited documents at the current stage can be divided into two main categories:

- (i) The impact of economic fluctuations caused by the COVID-19 pandemic on renewable energy

According to the cited literature on the effect of economic changes, we can divide it into two main aspects: promotion and suppression. The literature on promoting renewable energy development mainly focuses on the stock market and price fluctuations of traditional fossil energy such as oil. This change may bring opportunities for the development of renewable energy [28]. A noteworthy phenomenon is that many cited documents in this cluster are before 2020, that is, before the outbreak [29]. This reflects that academic research on traditional fossil energy will also affect renewable energy development [30]. On the other hand, many scholars have reached a consensus: due to the social distancing caused by the pandemic, self-isolation and travel restrictions have forced the reduction of labor in all economic sectors and led to the loss of many jobs. This has led to a slowdown in construction and decreased transactions in many sectors of society, including renewable energy-related construction [31].

The adoption of isolation measures has reduced human activities, which has brought short-term improvements to the environment, especially air quality [32–34]. Renewable energy has the same characteristics as being environmentally friendly and reducing pollutant emissions. Therefore, the improvement of the environment during the pandemic, especially for air quality [35,36], has also become an essential reference for scholars to conduct research. However, there are also cited documents that show that the emergence of the COVID-19 pandemic does not contribute to the improvement of the environment, which reflects another point of view that scholars are researching renewable energy and the environment [37].

4.2.2. Keyword co-occurrence analysis

This section first uses VOSViewer to draw the co-occurrence map based on text data. As shown in Fig. 5, it is evident that the pandemic has brought "opportunities" and "crisis" to the development of renewable

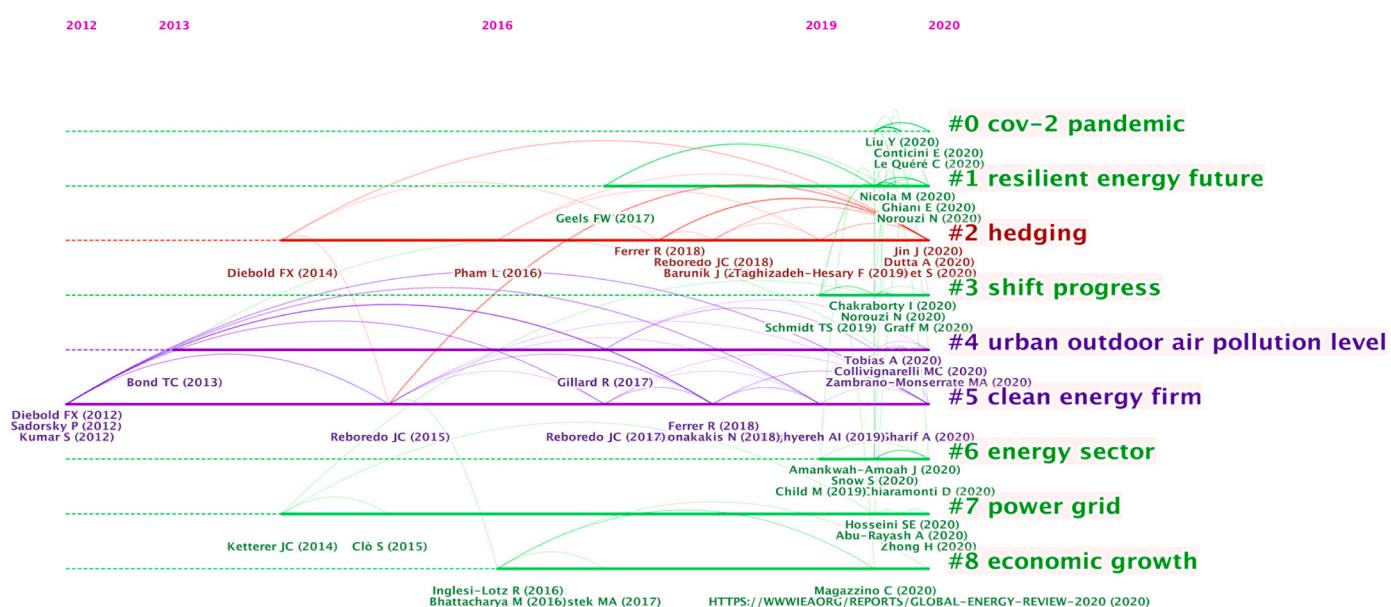


Fig. 4. Publication co-cited timeline visual map.

- (ii) The impact of environmental changes on renewable energy research

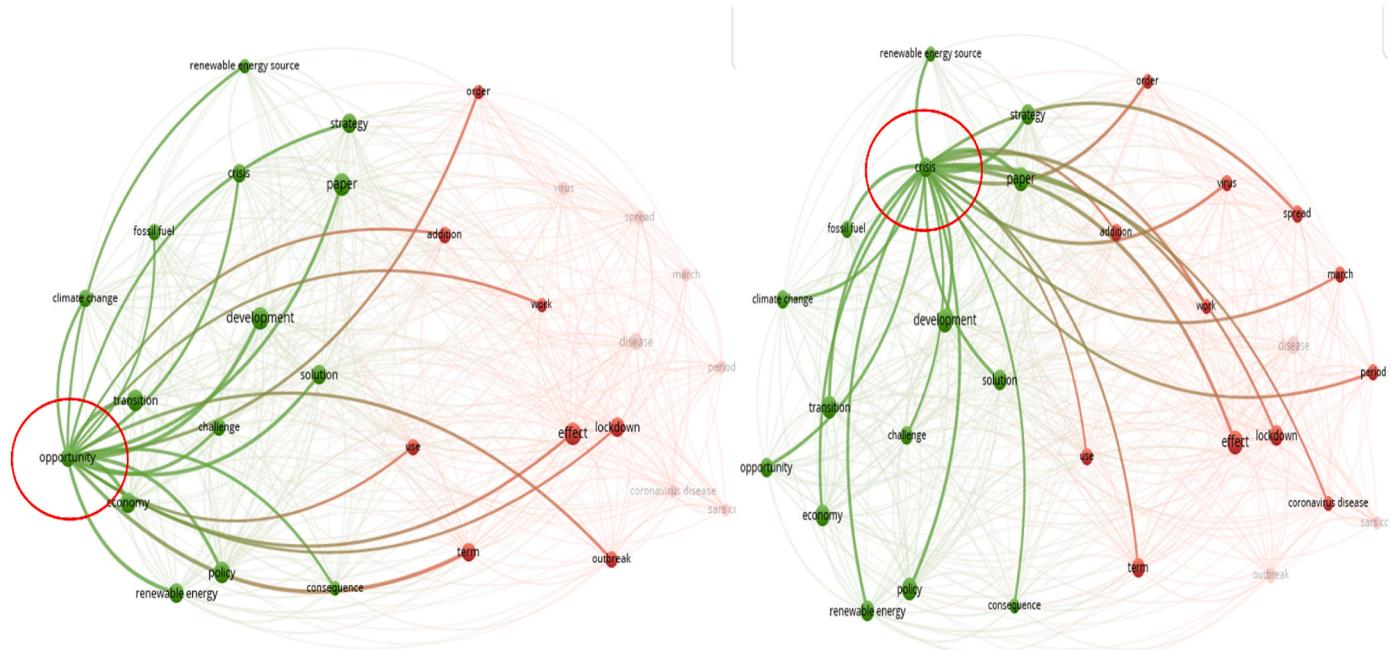


Fig. 5. The co-occurrence map of text data in COVID-19.

(i) Sustainable development

(a) Development opportunities obtained by renewable energy in sustainable development

energy. This reflects the duality brought about by the outbreak of the pandemic. To further study the response of research hotspots to the pandemic, we conducted a keyword co-occurrence analysis on the publication's keywords. After obtaining the sub-clusters by secondary clustering, further analysis is carried out by the two main aspects of "opportunities" and "crisis".

In Fig. 6, most of the countries facing electrification challenges are concentrated in developing countries in Asia and Africa before the

epidemic. In Fig. 6, the orange part represents 18 countries facing electrification challenges in Africa, and the yellow part represents 5 countries facing electrification challenges in Asia. The graphs represent population without electricity access since 2010 in Asia, Africa and the rest of the world. This situation has improved during the pandemic. Southeast Asia has created jobs, promoted economic growth, and resisted risks by increasing clean energy investment. As part of the investment in Southeast Asian countries, investment in renewable energy

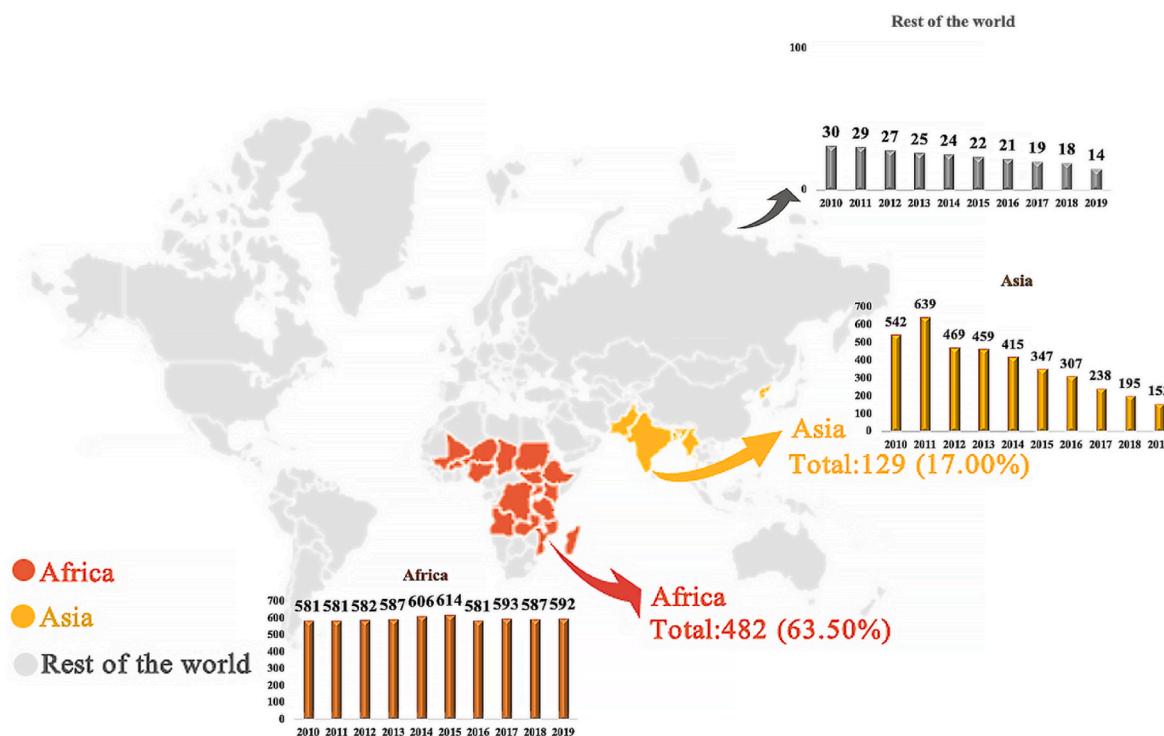


Fig. 6. Population without electricity access (millions) [42].

will support the achievement of SDGs7, further strengthen and regionalize the upstream and downstream manufacturing value chains [38]. South Asia is the gathering place of countries with the largest energy deficit globally. Data show that 152 million people in this region lack electricity and 900 million people lack the opportunity to clean cooking. South Asian countries use this moment of the pandemic to strengthen sustainable energy policies and use funds to accelerate economic recovery, narrow the gap in energy access, and improve the lives of disadvantaged populations in the region. This will directly support the realization of SDGs7 [39,40]. All this reflects that the pandemic has brought new opportunities for renewable energy development. Besides, we find that the occurrence of the pandemic has also affected the main research hotspots in this field. Before the outbreak of COVID-19, scholars' research on the sustainable development of renewable energy focused more on the technical level. After the outbreak, more scholars began to pay attention to renewable energy's social benefits role in corporate, social, and corporate governance [41].

(b) Renewable energy face challenge in sustainable development

Renewable energy services are the key to preventing and fighting the COVID-19 pandemic. There are five clusters of different colors in Fig. 7, which represent clusters formed by keywords of similar categories. Each node represents a different keyword, and the size of the node represents the frequency of the keyword. Links between keywords are marked with lines. We will highlight the keywords related to "renewable energy" and "sustainable development". For example "sustainable development", "COVID-19". These keywords are closely related to "investments" and "climate change". In Fig. 7 we can find, with the spread of the pandemic, the SDGs globally, especially in developing countries, have been

affected. With the spread of the virus, many countries have adopted social distancing and home isolation measures. These measures are initially based on an important assumption: People can use reliable and affordable electricity to stay in touch and communicate remotely through public services [43]. However, the blockade measures have slowed down the construction of renewable energy infrastructure and off-grid decentralized renewable energy planning, which affected the feasibility of this assumption. The frustration of renewable energy development will also affect realizing other sustainable development goals. The lack of cold chains and refrigeration means that the disadvantaged in rural areas cannot obtain vaccines, and the lack of energy prevents people in poor areas from cooking or cooling buildings.

(ii) Carbon emission

(a) The positive effect of the use of renewable energy on carbon emission

The green bars in Fig. 8 represent the global average annual change in energy-related CO₂ emissions for each year. During the period 1990–2019, the value rose and fell. However, the occurrence of the COVID-19 pandemic has caused a sharp decline in carbon emissions in 2020. This is mainly due to isolation measures affecting the transportation sector's emission reduction effect [44]. However, from the recovery of the world economy after the global financial crisis in 2009, we find that consumption has increased rapidly after the end of the pandemic, and global CO₂ emissions could rebound sharply [45]. Structural reforms on the supply side and improvements in production efficiency play a fundamental role in reducing carbon emissions. Increasing the proportion of renewable energy consumption is considered an effective way to achieve this result [46,47]. Also, the latest

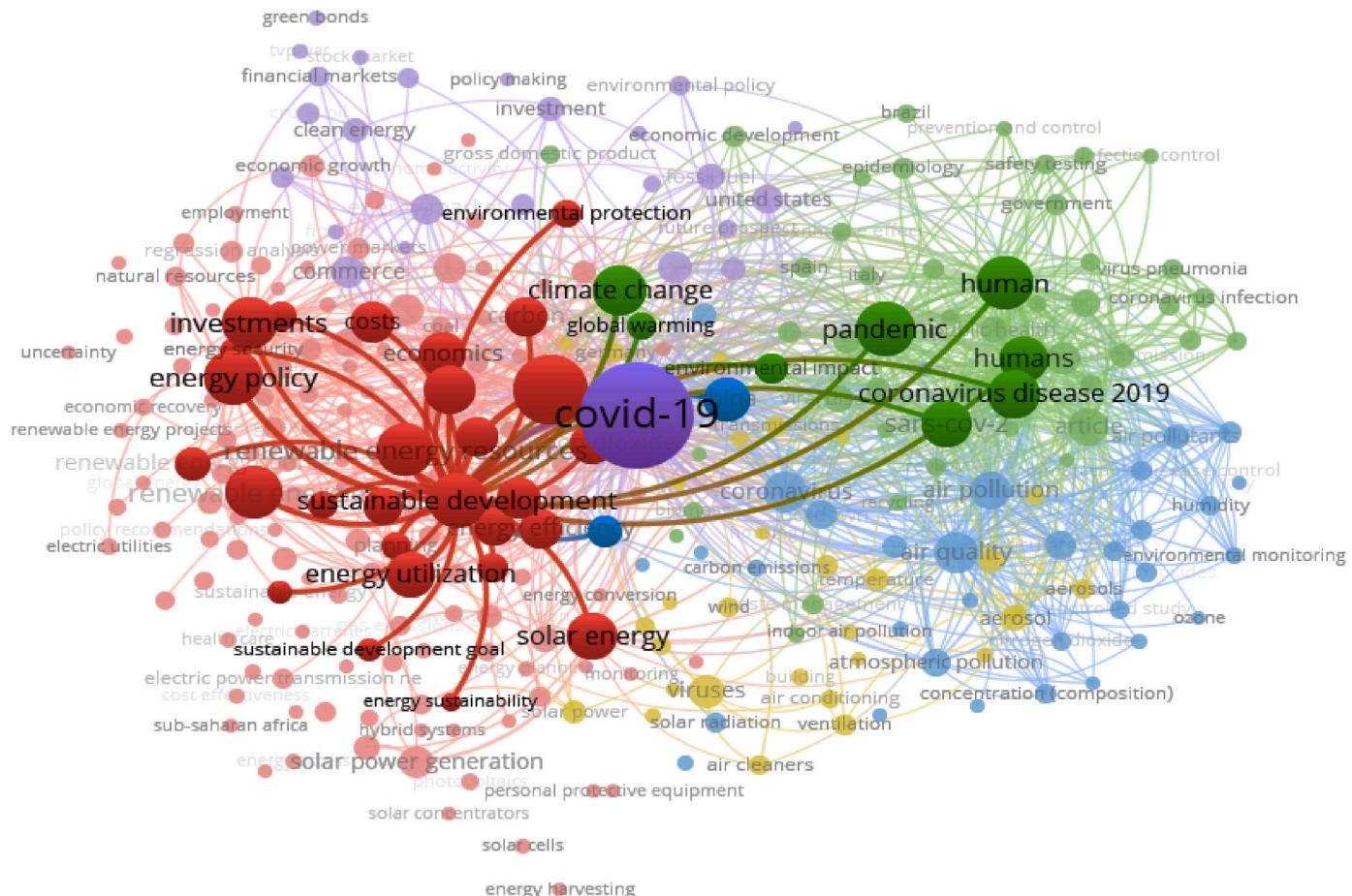


Fig. 7. The cluster view of the keyword network about sustainable development.

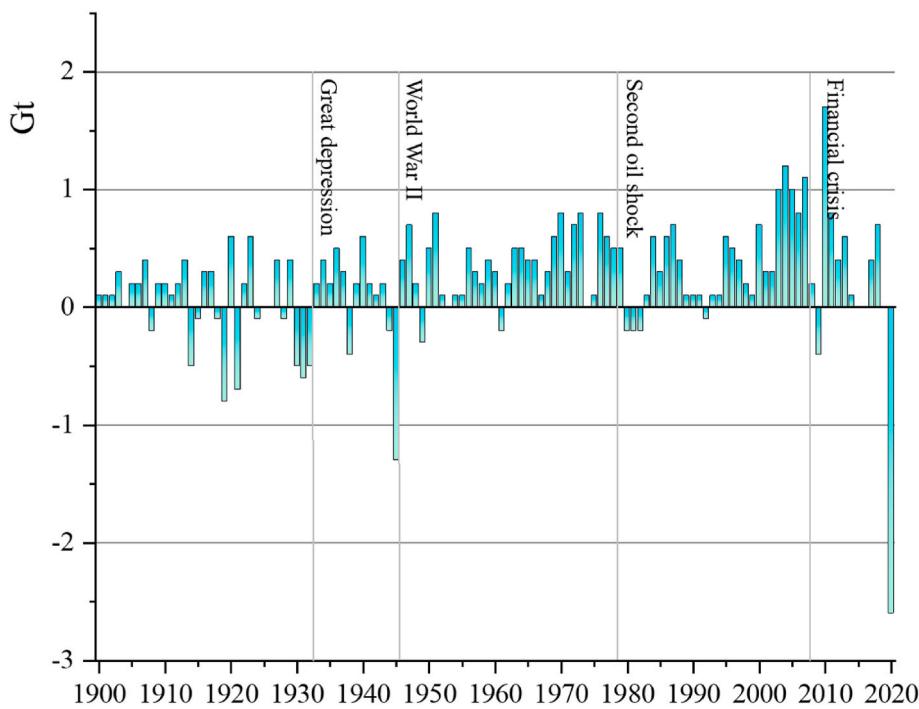


Fig. 8. Annual change in global energy-related CO₂ emissions, 1900–2020 [49].

economic and policy research results show that investment in low-carbon infrastructure has become an effective way to revitalize the economy after the pandemic [48].

(b) The negative impact of the pandemic on the carbon emission of renewable energy

In Fig. 9, the nodes related to carbon emissions are small, the distribution is relatively scattered, and there are not many connections with other keyword nodes, which is not conducive to the achievement of carbon neutrality goals. Although global carbon dioxide emissions declined in 2020, this decline will only be temporary if structural changes are not made to the energy system [50]. Even more severe is that the COVID-19 pandemic has affected the low-carbon transition of renewable energy in legislation and transactions. The legislative vote for eliminating coal in Germany and the landmark green agreement implemented in Europe face delays at different times, which may delay

the first wave of coal power capacity closure. From a trading perspective, since Italy implemented national pandemic prevention measures, prices in the European carbon trading market have shrunk by one-third. The current crisis may also pose a risk to heavy industry emission reduction. As heavy industry's profit margins are stricter, the emergence of the COVID-19 pandemic has focused attention on resuming production and maintaining the company's survival [51]. Given the long investment cycle of heavy industry, funding constraints may slow down or cancel the promotion of clean energy industrial technologies that produce almost no emissions, which threaten significant efforts to achieve long-term emissions reduction in the heavy industry [52].

(iii) Solar photovoltaic power

(a) The rapid development of solar energy during the pandemic

COVID-19 has a devastating impact on hundreds of millions of poor rural households. Through targeted social assistance and off-grid

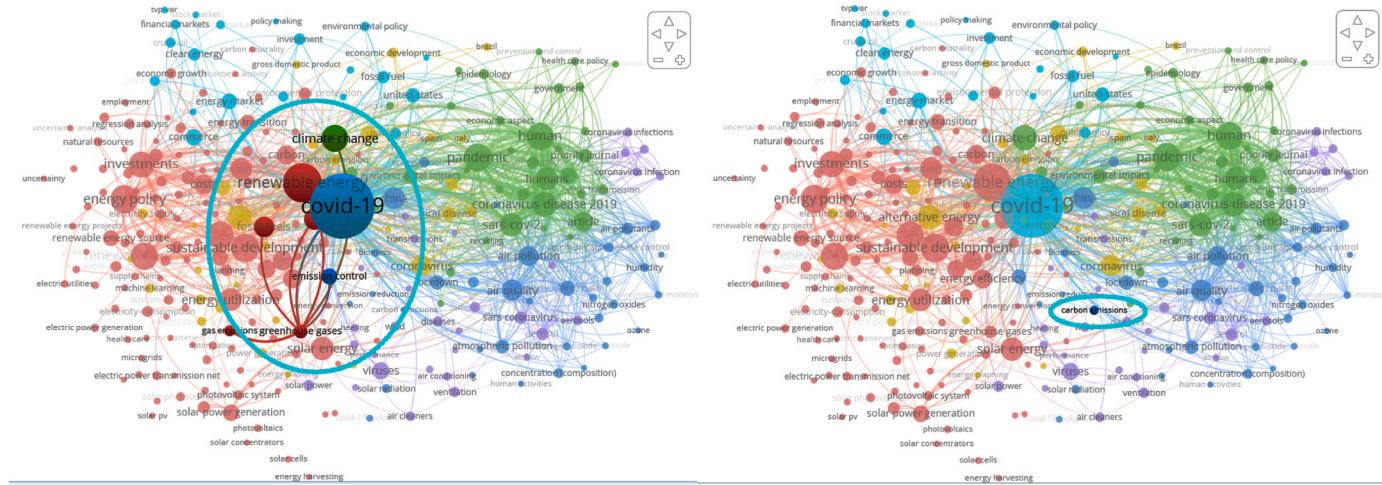


Fig. 9. The cluster view of the keyword network about carbon emission

technology solutions, solar power not only solves the problem of energy poverty [53], but also increases their ability to resist disease risks [54]. Solar PV and battery storage-based distributed energy resource (DER) are more resilient and cost-effective during the crisis [55], which has become the key to the fight against COVID-19 in rural areas in many developing countries [56]. Fig. 10 shows the important role that solar power plays in power generation. During the COVID-19 pandemic, oil consumption has dropped significantly. Due to energy supply safety, solar photovoltaic power generation provides the lowest cost electricity in history, posing a challenge to existing fossil fuel power plants. Overall, it is estimated that by 2025, renewable energy will account for 95% of the net increase in global power generation.

(b) The epidemic hinders the development of solar energy

The supply chain disruption and construction slowdown caused by COVID-19 and the increase in macroeconomic risks have made not all countries show a positive trend in photovoltaic power generation. Taking India as an example, the interruption of COVID-19 has led to a significant slowdown in PV deployment in 2020. The installation of new PV capacity is 70% lower than the average year-on-year growth of the previous three years; China (the world's largest photovoltaic market), the United States, and other countries' distributed photovoltaic markets show signs of weakness [57]. Besides, the uncertain subsidy policy during the pandemic has also affected private companies in the solar power industry [58]. First, the supply of solar system components (such as solar panels and batteries) is interrupted, making energy companies

face challenges in expanding energy supply during the pandemic [37]. Secondly, although some countries have announced intervention measures to solve the problem of energy insecurity, the influx of large amounts of funds may disrupt the balance between companies in the solar energy service industry, causing many operators to withdraw from the market, and utility-scale projects are stagnant. This will further affect the installed solar energy system, causing more consumers to fall into energy poverty [59,60].

(iv) Wind power

(a) The rapid development of wind energy during the pandemic

The links to "COVID-19" and "wind" in Fig. 13 indicate that due to the airborne form of the COVID-19 virus, the link between regional air pollution, wind energy use, and pandemic prevention and control has attracted researchers' attention [61–63]. As shown in Fig. 11, a case analysis from Italy finds relatively few cases of COVID-19 in cities with high wind energy production. In contrast, inland cities with serious air pollution and low wind energy use have more cases and deaths. This shows that increasing renewable energy production also promotes public health improvement [64]. Since offshore projects have a more extended construction period than onshore projects [65], the delays caused by the COVID-19 crisis have only slightly affected the offshore wind power industry. Driven by further reductions in costs, the annual increase in offshore wind power has surged. Offshore wind energy has the potential to meet today's global energy demand more than four times, foster a blue economy, bring employment opportunities and other

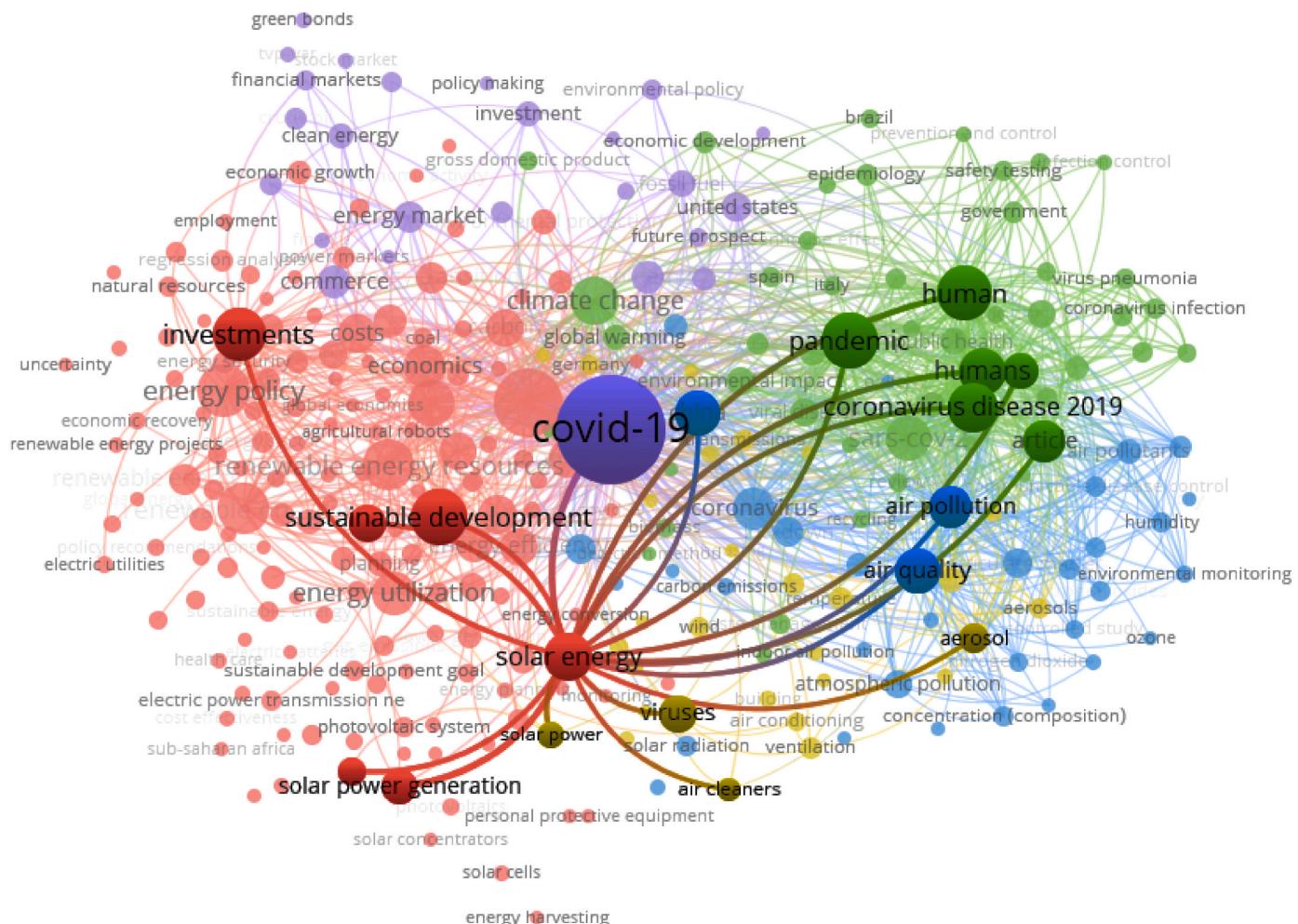


Fig. 10. The cluster view of the keyword network about solar energy.

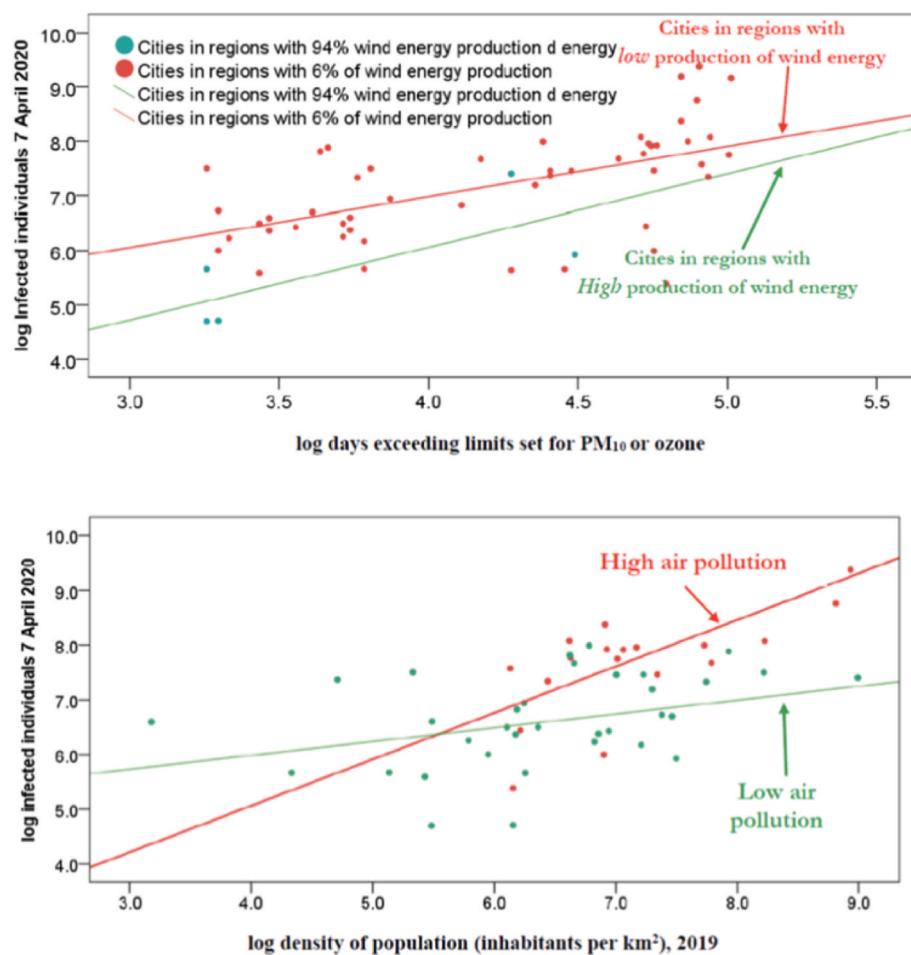


Fig. 11. Regression lines of log cases about air pollution and wind power [62].

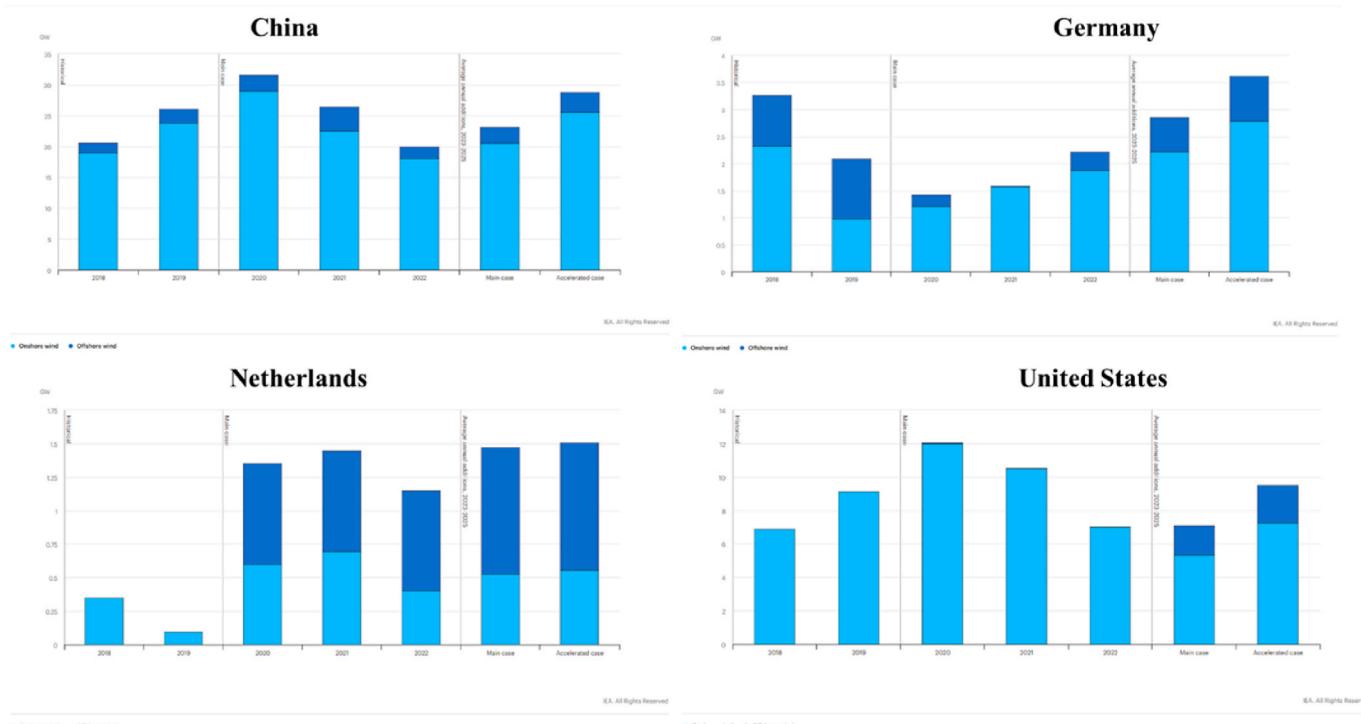


Fig. 12. Annual wind capacity additions 2018–2022 and average annual additions 2023–2025.

socio-economic benefits to some of the most vulnerable areas of climate change (such as small island areas and coastal areas). The predictability of offshore wind energy complements renewable energy variability, a compelling reason for making wave and tidal energy technologies an essential power system. Fig. 12 shows the annual wind power additions in the four countries. From the perspective of application scope, offshore wind power's growth scope has shifted from Europe to emerging markets such as China and the United States, and these markets have shown great potential.

(b) Obstacles to the development of wind energy during the pandemic

The long auction process and stagnant utilities hinder the projects being developed impacts wind energy projects in developed countries such as Australia, Germany, and Denmark and has a more significant impact on developing countries such as the Middle East and North Africa that mainly rely on bilateral contract development projects.

Fig. 14 shows the improvement of the environment during the pandemic by renewable energy is mainly concentrated in two aspects: air pollution and climate change. The quarantine measures taken by various countries due to the pandemic have brought environmental improvements, which to a certain extent promoted the development of renewable energy. Many regional or sub-city spatial analyses have appeared in publications, such as Beijing-Tianjin-Hebei in China [66],

Taiwan in China [67], Zakopane City in Poland [68], this reflects a certain extent that the relationship between renewable energy and air quality may be affected by the climate, industrial characteristics, and policies of different regions. Taking solar photovoltaic power stations as an example, the air pollution has dropped significantly. The air is cleaner, and more sunlight can pass through the atmosphere, thereby increasing the output of photovoltaic installations [69], enable distributed energy storage infrastructure to develop [70]. The impacts of renewable energy and climate change are mutual. The transition from fossil fuels to renewable energy is the basis for curbing human-made climate change [71], reducing carbon emissions to a certain extent. Various governments have assumed the role of actors and have successively issued a series of policy recommendations.

(b) Restrictions on renewable energy during the pandemic caused by environmental changes

Due to the fragility of renewable energy production [72,73], climate change will also affect its development and utilization, and these problems have become more prominent during the pandemic. During the pandemic, some scholars discovered that renewable energy to mitigate climate change also has negative environmental impacts. Focusing only on greenhouse gas emissions may ignore other negative environmental impacts, leading to undesirable side effects.

Although there have been a certain number of publications in

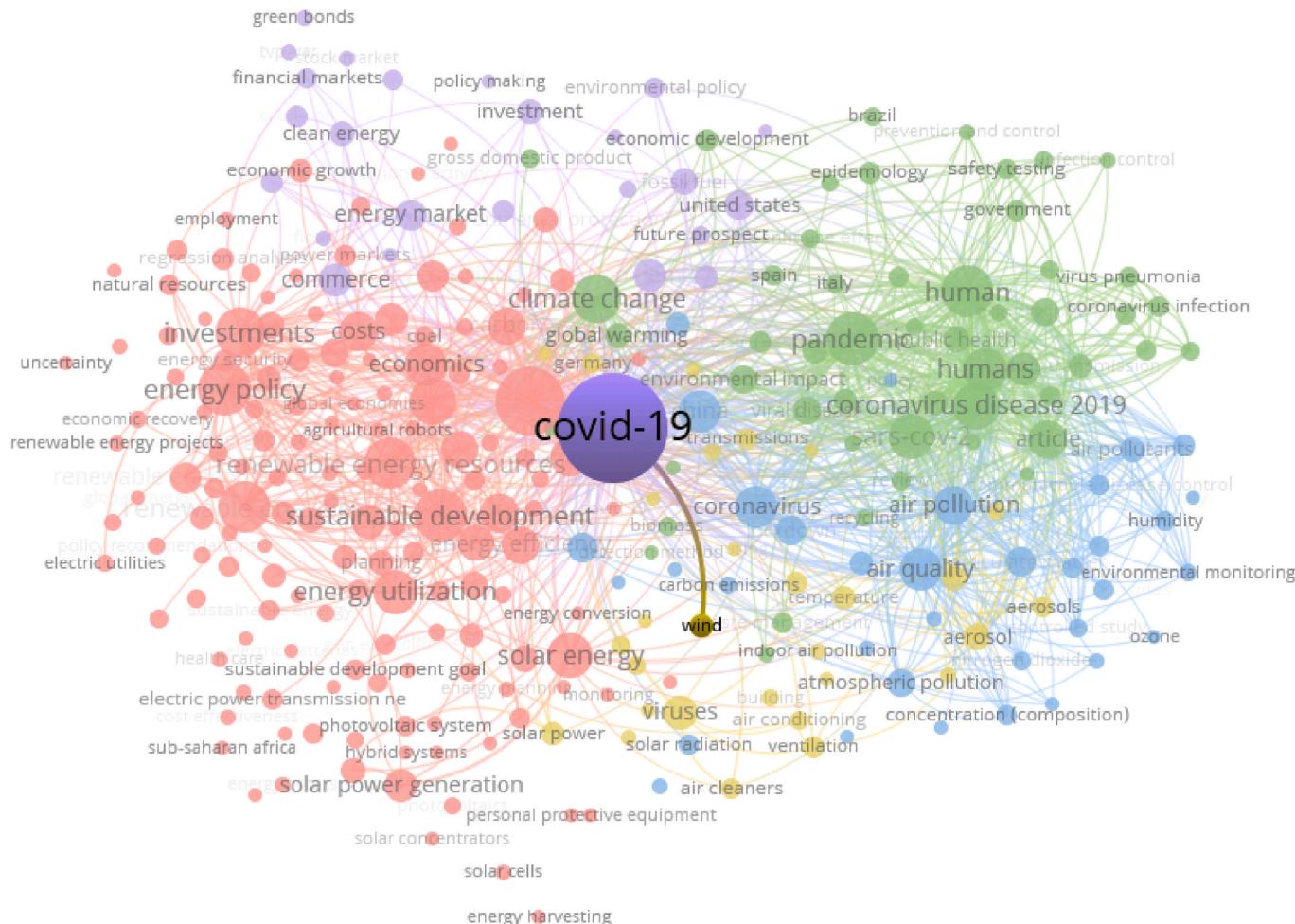


Fig. 13. The cluster view of the keyword network about wind energy.

- (v) Environmental management
- (a) Mutual promotion of renewable energy and environmental improvement

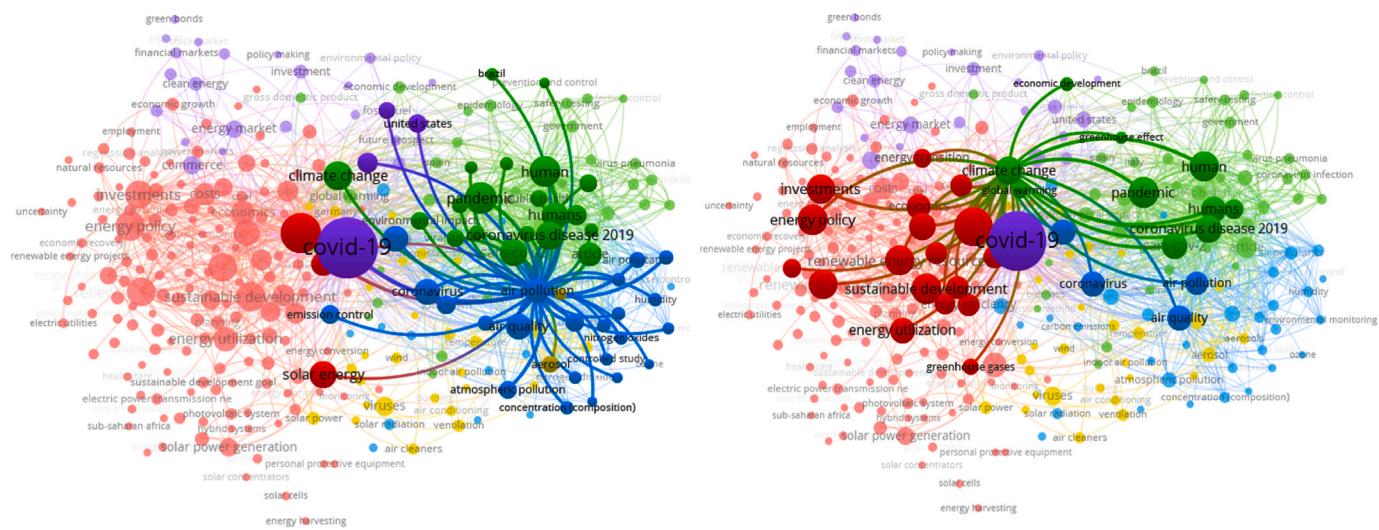


Fig. 14. The cluster view of the keyword network about environment management.

renewable energy since the beginning of the COVID-19 pandemic, there are still few systematic, methodologically sound and theoretical studies. To more intuitively reflect the opportunities and challenges encountered by renewable energy during COVID-19, Table 2 organizes the highly cited papers in Fig. 4. First, the emergence of the COVID-19 pandemic has won a window period for adjusting the energy structure. Before the pandemic outbreak, rapid economic growth prompted rapid growth in energy demand. Under the background that energy demand is greater than energy supply, it is more difficult to adjust the energy supply side structure. The implementation of blockade measures during the pandemic caused many international agencies to lower their energy demand. Countries worldwide have more opportunities and time to promote the green transition of energy. Economic stimulus measures for clean energy can directly or indirectly support renewable energy development. The second point is that falling energy prices are expected to increase emerging markets for renewable energy. According to IRENA statistics [74], as of the end of 2018, the cost of renewable energy such as hydropower, onshore wind power, biomass, geothermal, and photovoltaics was close to the lowest level of new fossil energy power generation, indicating that even in the absence of additional financial subsidies, these renewable energy, and fossil energy are initially equally competitive. The further drop in costs has created favorable conditions for attracting more participants into the renewable energy market. Of course, some “black swan” incidents due to social instability and the blockade of border bilateral cooperation will also bring new challenges to renewable energy development. Generally speaking, in the post-pandemic period, the recovery of fuel demand and strong government policies are expected to stimulate the energy industry's continued growth through 2025.

4.2.3. Keyword evolution analysis

Our research on the keyword map find that some keywords with high centrality did not become a research hotspot before the pandemic. We use CiteSpace to draw the keyword evolution map and list the top 20 keywords to further study this change. As shown in Fig. 15, we map the research sub-fields into a two-dimensional space according to the center level and density level of each cluster [93], and further use the strategy map method to explore the evolution trend of research hotspots in the field of renewable energy in the post-pandemic era. By sorting out the evolution of renewable energy keywords, smart energy systems play a key role in promoting renewable energy investment and improving renewable energy efficiency in the post-pandemic era. As a black swan event, the COVID-19 outbreak has greatly affected employment, upstream supply chains, and investor confidence in the clean energy

industry. The single energy sector has been unable to cope with the rapidly changing supply and demand of renewable energy. On the other hand, smart energy systems include all sectors or all energy carriers through a cross-sectoral integration approach, resulting in a more robust renewable energy ecosystem. We analyze from “renewable energy investment” and “renewable energy efficiency” as follows:

4.2.3.1. Quadrant 1.

(i) Renewable energy investment

High centrality keywords related to economy and finance such as “investment” and “economic condition” in Table 3 reflect that during the COVID-19 pandemic, investment in renewable energy may become a powerful engine for economic recovery after the COVID-19 crisis [95]. The blue mark in Fig. 17 is the evolution of energy investment. The United Nations Environment Programme’s report shows that COVID-19 has seriously impacted the fossil fuel industry. At the same time, renewable energy is more cost-effective than ever, and clean energy is one of the “most cost-effective” investments in countries’ economic recovery [96]. Investing in smart energy systems can achieve higher long-term cost savings and job creation than traditional fiscal strategies, with positive multiplier effects on the economy and the job market. For example, the Polish industrial sector’s power system selects renewable energy to overcome the limitation of the negative impact of greenhouse gas emissions on the environment [97]. Besides, renewable energy consumption can promote sustainable economic growth and environmental improvement, enhance the country’s image on a global scale, and open up international trade opportunities with environmentally friendly countries [98]. The economic recovery plan designed in response to the economic recession caused by COVID-19 provides an opportunity for the traditional energy structure to transform into sustainable energy [80]. First, investing in renewable energy can avoid the problem of fossil fuels trading high environmental costs for short-term benefits [14]. Cost-effective renewable energy investments accelerate the nation’s transition to a zero-carbon economy [99]. Secondly, clean energy and low-emission infrastructure investment will accelerate the sustained stability and growth of low-carbon alternatives [100].

In January–October 2020, China, India, and the European Union promoted the global auctionable renewable energy power generation, which increased 15% over the same period last year. The data growth shows that investors may have strong demand for renewable energy in the medium and long term. As shown in Fig. 16, the publicly listed stocks of renewable energy equipment manufacturers and project developers

Table 2
Summary of research questions and opportunities.

Theme of the studies	Research questions and opportunities	Ref.	Study area	Research methods	Other suggestions for future research
Renewable energy sustainability and COVID-19	17 Sustainable Development Goals (SDGs)	1.Sustainability and development after COVID-19 [75]	Developing countries Worldwide	Theoretical analysis	1. Comparative analysis of countries with different social and economic development levels. 2. Use raw economic data available globally
	Shape the politics of sustainable energy transitions	2.Covid-19 and the politics of sustainable energy transitions [76]		Broad multi-scalar and multi-actor approach	
	The impact of sustainability on investment	3.Covid-19 and Optimal Portfolio Selection for Investment in Sustainable Development Goals [77]	Worldwide	Theoretical Model of SDG Investment and Portfolio Selection	
	Clean energy transition	4.COVID-19 energy sector responses in Africa: A review of preliminary government interventions [78]	Africa	International organization and government report analysis	
	Smart grid, transportation system, charging station network and sustainable city development, fossil fuel subsidies, green transformation	5.Green the Post-pandemic Recovery in the G20 [79]	United States, South Korea	Case analysis	
	Carbon neutral	6.Navigate the Clean Energy Transition in the COVID-19 Crisis [80]	Worldwide	Policy Analysis	
	Sustainable Development Goals	7.Contextualize the Covid-19 pandemic for a carbon-constrained world: Insights for sustainability transitions, energy justice, and research methodology [37]	Worldwide	Collect world data	
	Volatility spillovers and co-movements among energy-focused corporations	1.Co-movements and spillovers of oil and renewable firms under extreme conditions: New evidence from negative WTI prices during COVID-19 [81,82]	Global renewable energy and coal market	the spillover index approach	1.Use data from countries with different levels of development. 2.Classification of different energy portfolios
	PV	2.The post COVID-19 green recovery in practice: Assessing the profitability of a policy proposal on residential photovoltaic plants [70]	Italy	Economic evaluation	
	Low carbon investment	3.COVID-19 recovery funds dwarf clean energy investment needs [83]	Worldwide	Classify and compare governments' fiscal stimulus plans	
Renewable energy and power system	Green and low-carbon energy transition	1.An outlook on the global development of renewable and sustainable energy at the time of COVID-19 [10]	Worldwide	Theoretical analysis	1.Model and empirical analysis. 2.Big data mining and analysis. 3.Conceptualization of the research
	Load profiles, electricity consumption and market prices in Italy, including the environmental aspects	2.Impact on electricity consumption and market pricing of energy and ancillary services during pandemic of COVID-19 in Italy [84]	Italy	Case analysis	
	Changes in the proportion of renewable energy and carbon dioxide emissions	3.Electricity demand during pandemic times: The case of the COVID-19 in Spain [85]	Spain	Case analysis	
	Investment in clean energy in the power industry	4.Implications of COVID-19 for the electricity industry: A comprehensive review [86]	Worldwide	Comprehensive review	
	The impact of government restrictions on electricity load, power generation and transmission	5.Impact analysis of COVID-19 responses on energy grid dynamics in Europe [87]	Europe	Case comparison	
	PV	6.Effect of COVID-19 virus on reducing GHG emission and increasing energy generated by renewable energy sources: A brief study in Malaysian context [88]	Malaysia	Data analysis	
	Carbon emission	1.The Short-run and Long-run Effects of Covid-19 on Energy and the Environment [89]	Worldwide	Data analysis	1. Microdata analysis. 2. Building new theory on pandemic disruption management, leveraging the existing theories
	Environmental change and environmental policy	2.A brief review of socio-economic and environmental impact of Covid-19 [90]	Worldwide	Report analysis	
	The positive and negative effects of the environment	3.Effects of Covid-19 outbreak on environment and renewable energy sector [91]	Worldwide	Literature review	
	Air pollution	4.How (Un)sustainable environments are related to the diffusion of covid-19: The relation between coronavirus disease 2019, air pollution, wind resource and energy [92]	Italy	Case analysis	

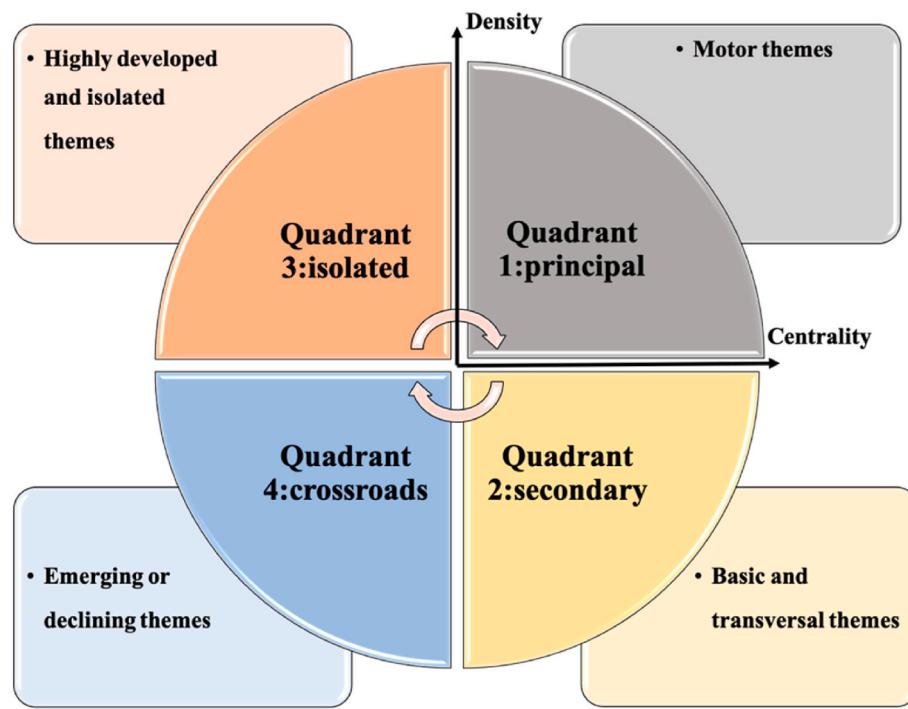


Fig. 15. The strategic diagram [94].

Table 3

The most representative top twenty keywords.

Keyword	Centrality	Degree	Freq
united states	0.66	4	4
prevention and control	0.48	6	4
investment	0.45	4	11
viral disease	0.43	5	14
carbon dioxide	0.41	7	6
betacoronavirus	0.36	7	8
pandemic	0.36	5	7
economic condition	0.35	3	4
human	0.34	7	18
coronavirus disease 2019	0.29	4	17
environmental economics	0.27	4	5
covid 19	0.26	3	47
climate change	0.25	3	14
article	0.25	4	12
economic and social effect	0.21	2	5
particulate matter	0.21	2	5
safety testing	0.2	5	4
renewable energy resource	0.18	5	11
public health	0.16	5	8
air pollution	0.16	3	7

have exceeded most major stock market indexes and the entire energy industry. The share prices of global solar companies more than doubled in October 2020 compared with December 2019. In addition to the government's public investment, investment in the private sector is also very important during the COVID-19 pandemic. On the one hand, various governments adjust market expectations through policy guidance, so that investors can foresee the prospect of investing in a low-carbon economy [101]. On the other hand, the government further accelerate integrating the internal energy market, strengthen international policy coordination, and ensure that energy prices remain stable and reasonable to attract investors' attention to the green energy industry.

4.2.3.2. Quadrant 2.

(i) Renewable energy efficiency

"Energy efficiency" and "safety testing" in Table 3 show that renewable energy efficiency has gradually attracted academic attention after the outbreak. While the pandemic has brought development opportunities to renewable energy, it has also exposed issues regarding renewable energy efficiency, renewable energy security, renewable energy subsidies, etc. For a global crisis similar to the COVID-19 pandemic, power security and resilient energy systems are even more critical [102]. After the outbreak, energy production systems, energy end users, energy distribution and storage systems, and intelligent energy management systems have all been impacted to varying degrees. But at the same time, the level of electrification and digitalization is also increasing [103]. The interaction from "home to network to city" can be realized through the intelligent energy system, covering the entire range from users to power generation systems, reducing losses and obtaining higher economic and environmental benefits [104]. In July 2020, European Commission launched an integrated development strategy for the EU energy system. Simultaneously, it promotes the establishment of industry alliances in many key areas such as clean hydrogen energy and batteries, improving energy efficiency by building smart energy systems. During the crisis in 2009, global energy-related carbon dioxide emissions fell by 2.2%. But then, with the help of a stimulus plan that focuses on the fossil industry and infrastructure, carbon dioxide emissions rebounded by 4.5% in 2010, setting the fastest annual growth rate in history [105,106]. Governments in Africa, for example, have reached a consensus: The COVID-19 pandemic has brought opportunities to strengthen the African continent's demand for a sustainable energy transition [57]. Investment in all areas of clean energy can provide considerable opportunities to increase employment and economic activity [107]. Post-pandemic stimulus expenditures must focus on renewable energy efficiency to support green recovery and realize a green energy economy [108], to prevent the recurrence of the 2019 financial crisis [109]. But we need to note that in Fig. 17, the energy efficiency research does not have a clear evolutionary context.

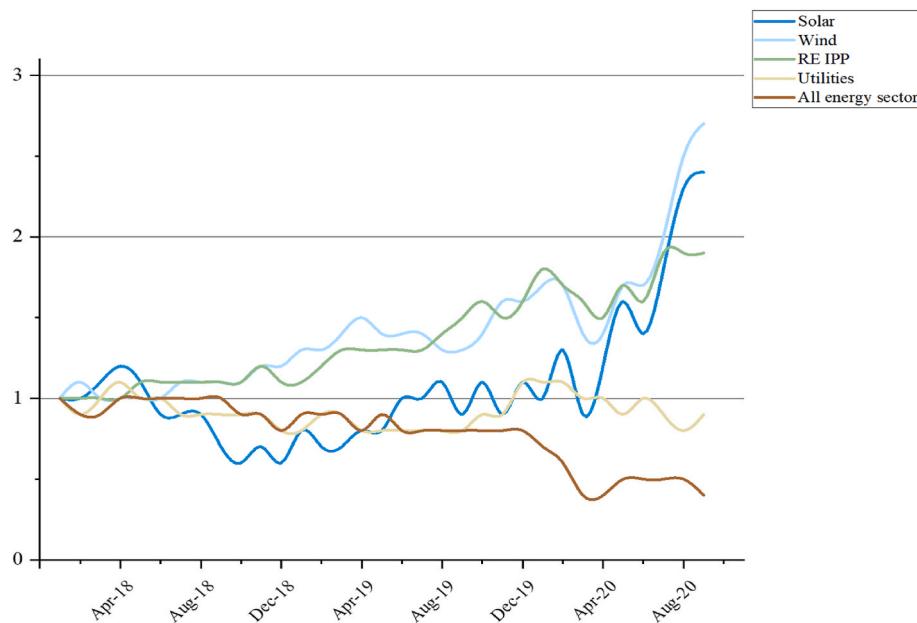


Fig. 16. Indexed stock market prices for traded energy companies, 2018–2020.

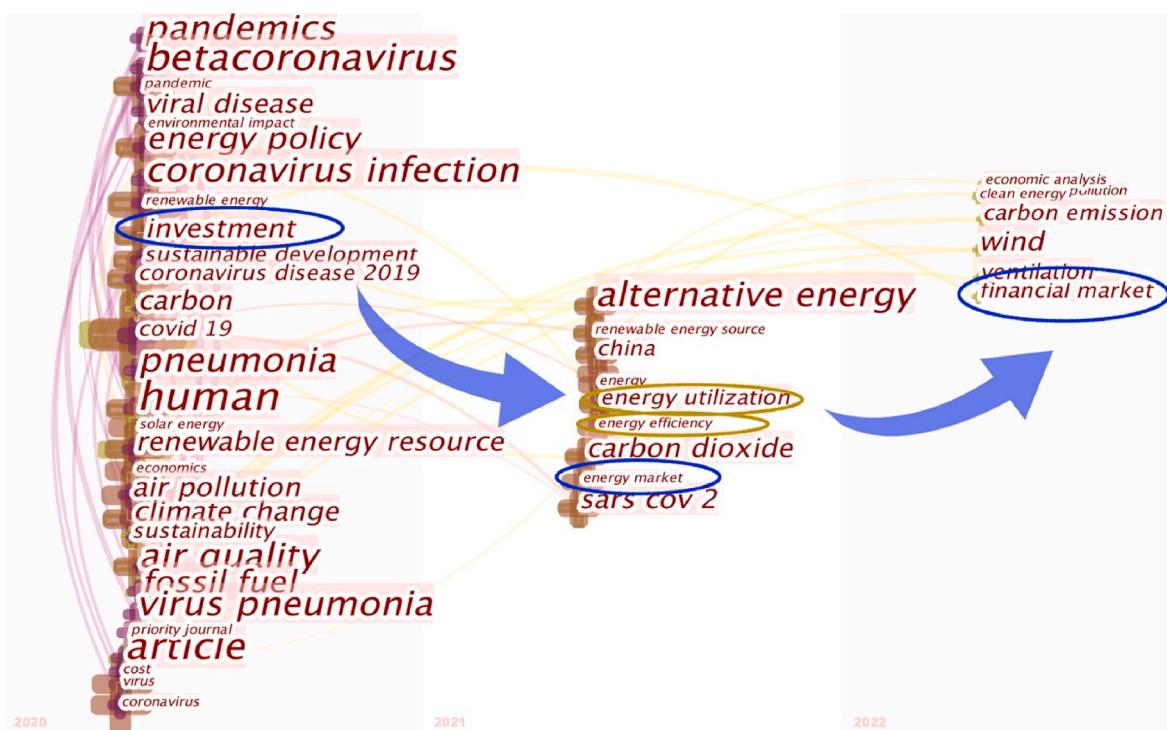


Fig. 17. Keywords evolution timezone diagram in COVID-19.

4.3. Future policy recommendations

To further summarize the focus of renewable energy research in different countries, we explore effective measures for smart energy systems to promote renewable energy development. In the following analysis, we use principal component analysis and multiple regression analysis to explore the development policy recommendations for countries with different characteristics. We classify the top 20 countries by the number of publications in the Scopus database according to the four sub-categories in 4.2.2. Addition to sustainable development, environmental management, carbon emission, solar photovoltaic power, wind

power 5 categories, we find a small number of publications researching investment in renewable energy, so we add “investment”. In terms of research methods, we use the unsupervised machine learning algorithm (principal component analysis) to complete the analysis of national research hotspots. The analysis process using Minitab software is shown in Fig. 18 below:

After using Minitab for principal component analysis, we analyzed the results according to Table 4 and Table 5. From the scree plot in Fig. 18, it can be found that from the second principal component, the change is horizontal and almost reaches 0, which also shows that two principal components are enough to meet the requirements for the

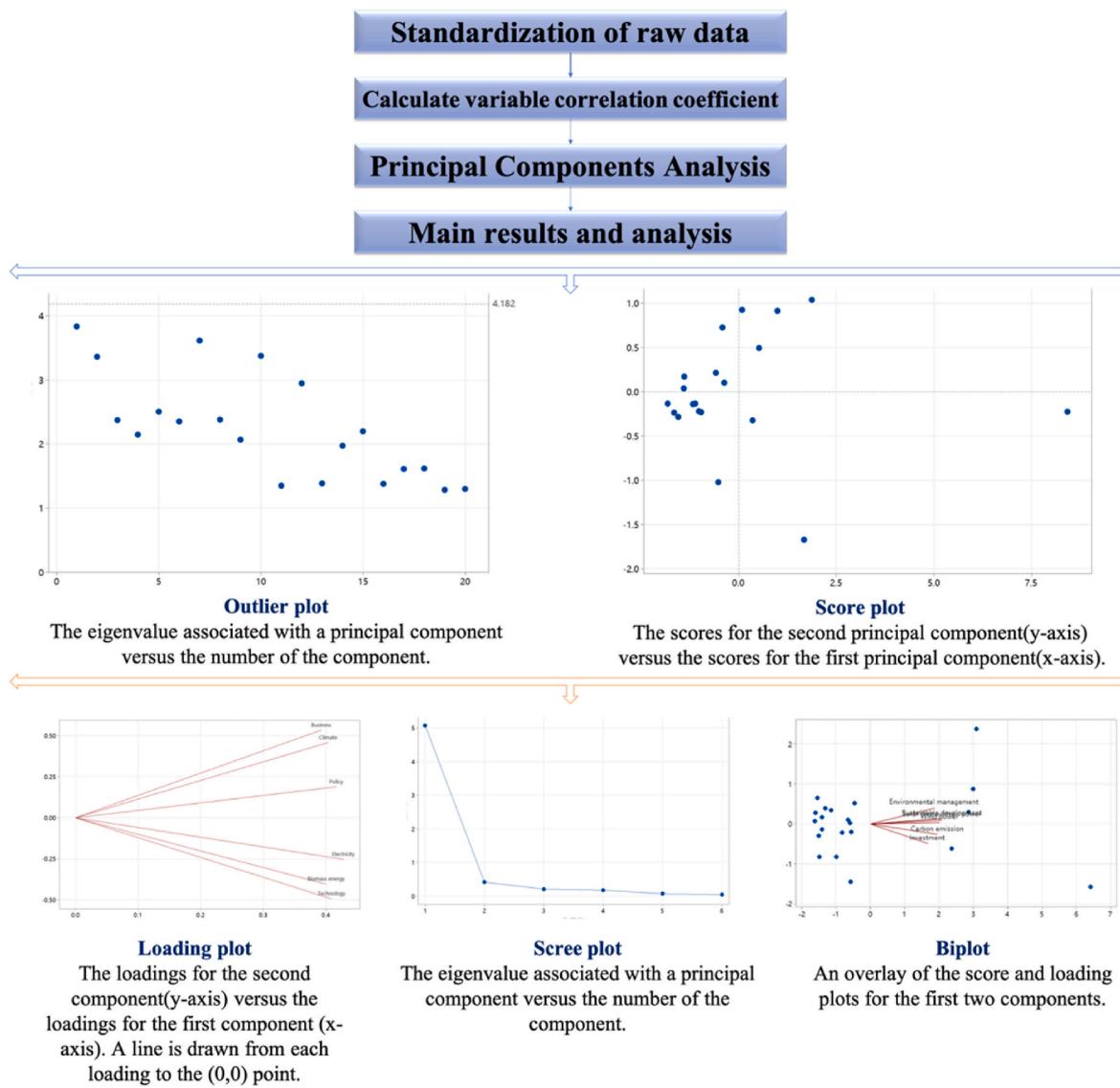


Fig. 18. Flow chart illustrating the steps involved in principal component analysis.

Table 4
Characteristic analysis of correlation matrix.

Eigenvalues	4.7859	0.7014	0.2889	0.1108	0.0667	0.0462
Ratio	0.798	0.117	0.048	0.018	0.011	0.008
Accumulation	0.798	0.915	0.963	0.981	0.992	1

selection of principal components. So here we consider keeping the first two principal components: sustainable development, environmental management. The eigenvectors corresponding to the six eigen roots of the correlation matrix are given in Table 4. Since the first two principal

components have reflected 90% of all the information, we only write the expressions of the first two components. The principal component analysis is carried out from the correlation matrix, and the variables Z1, Z2, Z3, Z4, Z5, Z6 in the principal component expression are standardized variables:

$$C1 = 0.437Z1 + 0.392Z2 + 0.408Z3 + 0.347Z4 + 0.439Z5 + 0.42Z6$$

Here, the number with the largest absolute value among the six coefficients is 0.439, which corresponds to “solar photovoltaic power”, indicating that it has the greatest influence among them.

$$C2 = 0.197Z1 + 0.567Z2 - 0.372Z3 - 0.692Z4 + 0.14Z5 + 0.053Z6$$

Table 5
Feature vector.

Variable	PC1	PC2	PC3	PC4	PC5	PC6
Sustainable development	0.437	0.197	-0.25	-0.211	-0.497	0.645
Environmental management	0.392	0.567	-0.223	0.212	-0.213	-0.62
Carbon emission	0.408	-0.372	0.472	-0.535	-0.252	-0.349
Investment	0.347	-0.692	-0.499	0.377	-0.01	-0.102
Solar photovoltaic power	0.439	0.14	-0.187	-0.352	0.789	0.081
Wind power	0.42	0.053	0.617	0.598	0.145	0.247

Here, the absolute value of the Z4 coefficient is 0.692 at most, so it means that “investment” contributes the most in this principal component.

Our research find that countries with a clear research focus have different characteristics. We use the number of people diagnosed with COVID-19 as an indicator of the impact of the epidemic, coal consumption as an indicator of dependence on fossil energy, and the national installed capacity of photovoltaic power generation as an indicator of renewable energy use, to explore the relationship between these three and the focus of the study. We perform multiple regression analysis according to Fig. 19 and presented the results in Tables 6–8.

Through the analysis results, we can see that the three types of countries have shown high enthusiasm for renewable energy investment, including the United States, which has been most affected by the epidemic. China, a traditional fossil energy consumer. Italy, which is relatively developed in renewable energy. The difference is that European and North American countries with more severe epidemics have conducted more research on sustainable development and environmental management. This is related to the continued increase in confirmed cases of COVID-19 that these countries face. Researchers are more likely to explore the path to social security and sustainable development. Traditional fossil energy consuming countries pay more attention to carbon emissions, solar photovoltaic power generation and wind energy. To a certain extent, this indicates that these countries have recognized that the COVID-19 epidemic has become a key node in the country's transition to zero-carbon energy, which plays a role in the construction of smart energy systems and energy transition. Countries with more developed renewable energy are more focused on environmental management and carbon emissions research. A notable phenomenon is that when $P < 0.05$, there is a good correlation between the two. Among the studies of the three types of countries we involved, only $P = 0.0062$ in fossil energy countries has a good correlation. Whether there is a regression relationship between the remaining two categories

Table 6
Analysis of variance.

	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Impact of COVID-19 pandemic	Regression	6	6.7935	1.13224	2.37	0.1094
	Error	10	4.7794	0.47794		
	Total	16	11.5728			
Dependence on fossil energy	Regression	6	12.0347	2.00579	38.71	0.0062
	Error	3	0.1555	0.05182		
	Total	9	12.1902			
Renewable energy use	Regression	6	5.64502	0.940837	0.96	0.5608
	Error	3	2.94207	0.980691		
	Total	9	8.58709			

Table 7
Model summary.

	S	R-sq	R-sq (adj)
Impact of COVID-19 pandemic	0.691332	58.70%	33.92%
Dependence on fossil energy	0.227643	98.72%	96.17%
Renewable energy use	0.990298	65.74%	0.00%

of countries and research categories still needs further research.

At last, according to the above analysis, we mainly focus on “solar photovoltaic power” and “investment” to give three types of countries’ development policy recommendations for building smart energy systems:

- (1) For countries severely affected by the epidemic, it is necessary to increase investment in renewable energy to maintain social security and stability. Investment in smart energy system infrastructure such as smart grids, electric vehicle charging, improved digital connectivity or bike lanes can have positive multiplier

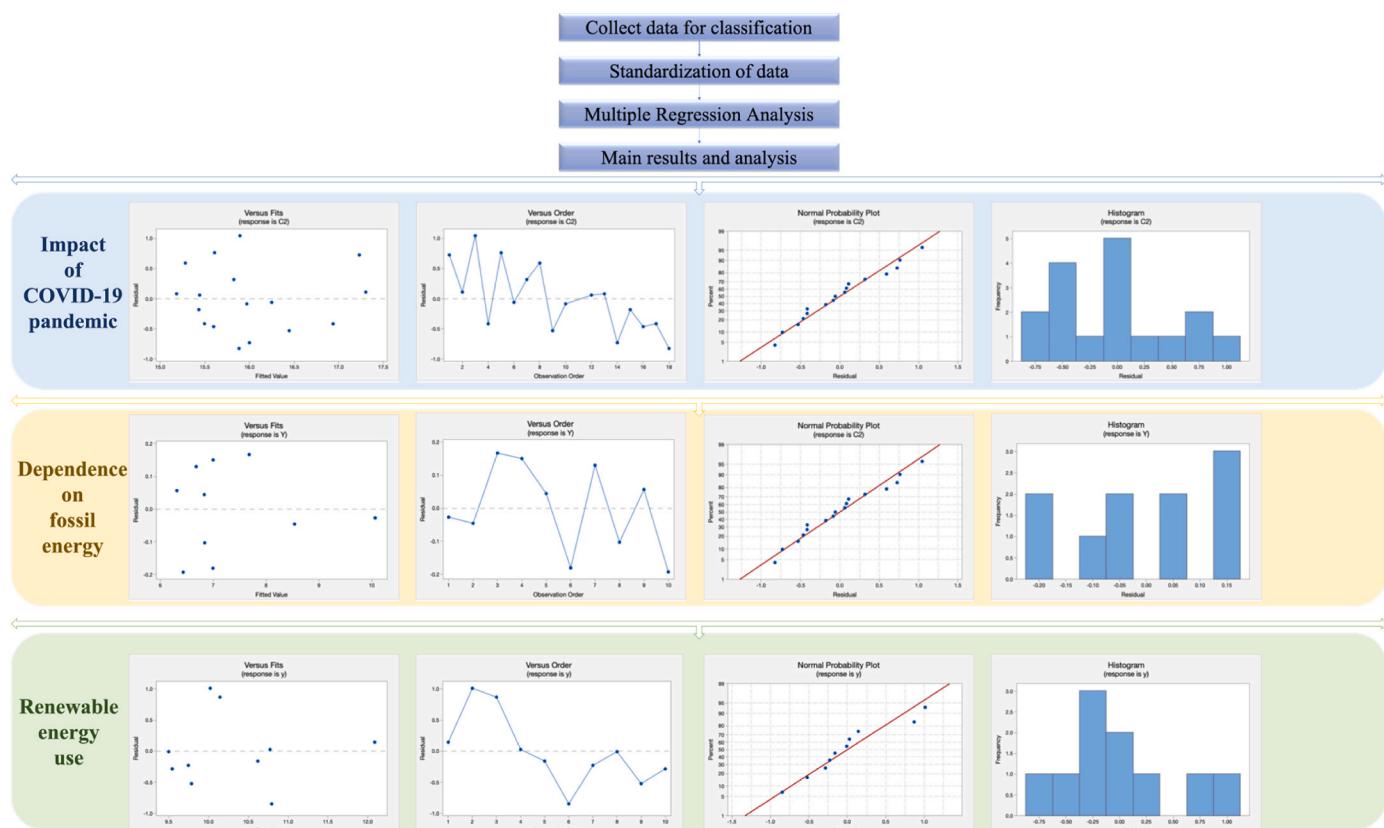


Fig. 19. Flow chart illustrating the steps involved in multiple regression analysis.

Table 8
Coefficients.

	Term	Coef	SE Coef	90% CI	T-Value	P-Value
Impact of COVID-19 pandemic	Constant	15.2872	0.2731	(14.7922, 15.7823)	55.97	<0.0001
	sustainable development	0.1301	0.1185	(-0.0846, 0.3449)	1.1	0.2978
	environmental management	0.0952	0.121	(-0.1241, 0.3145)	0.79	0.4498
	carbon emission	-0.0671	0.1448	(-0.3295, 0.1953)	-0.46	0.6529
	solar photovoltaic power	-0.1746	0.1595	(-0.4637, 0.1146)	-1.09	0.2996
	wind power	0.1549	0.1736	(-0.1598, 0.4696)	0.89	0.3933
Dependence on fossil energy	investment	0.0221	0.1153	(-0.1868, 0.2310)	0.19	0.8518
	Constant	6.1783	0.1386	(5.8523, 6.5044)	44.59	<0.0001
	Sustainable development	-0.00141	0.05922	(-0.14078, 0.13796)	-0.02	0.9825
	Environmental management	-0.31233	0.09054	(-0.52539, -0.09926)	-3.45	0.0409
	Carbon emission	-0.22648	0.07735	(-0.40852, -0.04445)	-2.93	0.0611
	Solar photovoltaic power	0.42734	0.08705	(0.22247, 0.63221)	4.91	0.0162
Renewable energy use	Wind power	0.411	0.1129	(0.1454, 0.6766)	3.64	0.0357
	Investment	0.04144	0.04334	(-0.06055, 0.14343)	0.96	0.4095
	Constant	9.2409	0.9406	(7.0273, 11.4546)	9.82	0.0022
	Sustainable development	-0.0746	0.2952	(-0.7694, 0.6202)	-0.25	0.8169
	Environmental management	0.0473	0.3705	(-0.8247, 0.9193)	0.13	0.9064
	Carbon emission	0.1889	0.364	(-0.6677, 1.0455)	0.52	0.6397
	Solar photovoltaic power	0.2119	0.3002	(-0.4945, 0.9184)	0.71	0.5311
	Wind power	-0.4311	0.57	(-1.7724, 0.9103)	-0.76	0.5044
	Investment	0.0684	0.3056	(-0.6507, 0.7876)	0.22	0.8372

effects on the economy and job market [103], enabling countries and businesses to achieve better economic returns and positive returns than traditional fossil fuel investments [110,111], while enhancing the resilience of their respective national energy systems.

- (2) Solar photovoltaic power generation can become the focus of smart energy system construction for traditional fossil energy consumption countries. The COVID-19 pandemic has introduced opportunities for structural change and the development of low-productivity and low-value-added jobs into the modern economy. Solar PV is emerging as the cheapest option for generating electricity in much of the world. Emerging and developing countries should maintain sustainability and environmental protection as guiding principles in the face of grid integration and mitigation policy, regulatory and financing challenges, rather than being a side effect of smart energy system construction [8]. In addition to general government, specific agencies should be set up to implement this objective. This ensures that despite changing political preferences, long-term vision and commitment must be an unalterable priority [112].
- (3) For countries that use large renewable energy, it is necessary to widen energy investment channels and maintain steady renewable energy investment growth. Green finance policies, such as carbon pricing, tradable green certificates (TGCs) and green credits, can provide low-cost financing and offset adverse impacts [16]. Among these countries, the construction of smart energy system not only includes production, distribution, use, and storage, but also establishes a cooperative platform to help countries formulate and achieve carbon neutrality goals, and the platform shares financial, technical and human resources. This could provide policymakers with a clearer signal, further encouraging the acceleration of global economic development.

5. Conclusion

This paper uses systematic literature review (SLR) and latent semantic analysis (LSA) to visually analyze the relevant research on renewable energy during COVID-19 in the Scopus database. Draw a knowledge visualization map to illustrate this field's current research status and development path. Then, we use the machine learning-based analysis (principal component analysis) to make suggestions for future development. The conclusion of this article is as follows:

- (1) Under the background of isolation measures and trade protectionism adopted by many countries, the collaboration between the Chinese government and the member states of the "the Belt and Road" initiative has shown an intensified trend. The strengthening of multilateral cooperation has played an essential role in alleviating the economic crisis and energy security issues caused by COVID-19 in developing countries.
- (2) Co-citation analysis through CiteSpace shows that the current cited literature no longer focuses on the pathological research and social impact of the early COVID-19 pandemic. Instead, it focuses on the two-way relationship between sustainable development, environmental management and renewable energy caused by the pandemic. This reflects that the field of renewable energy now has a relatively complete research framework. Then we conducted a co-occurrence study based on text data. The map showed two major directions of "opportunity" and "crisis" in the development of renewable energy during the pandemic. We further use VOSViewer to perform keyword-based co-occurrence analysis, obtain five sub-keyword clusters after the secondary clustering: sustainable development, environmental management, carbon emission, solar photovoltaic power, and wind power, analysis them from the two aspects of "crisis" and "opportunity". We use the strategic map analysis method and use the keyword timezone map to summarize two research hotspots: (1) Clean energy investment has become an important measure to revitalize the economy after the epidemic. (2) Energy efficiency research will effectively promote the sustainable development of renewable energy.
- (3) Through machine learning-based analysis, we find countries that are more severely affected by the epidemic focus more on sustainable development and environmental management research, traditional fossil energy consuming countries pay more attention to carbon emissions, solar photovoltaic power generation and wind energy, and countries with extensive renewable energy use pay more attention to environmental management and carbon emissions research. However, the regression relationship between the first two is not obvious. In the end, we find that smart energy systems can promote the development of renewable energy in the post-epidemic era, and put forward three types of development suggestions: (1) Increase investment in smart energy system infrastructure. (2) Promote the construction of solar photovoltaic power generation systems. (3) Establish an open and shared information cooperation platform.

Author contribution statement

Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Supervision, Writing- Reviewing and Editing. **Rui Huang:** Methodology, Software, Data curation, Investigation Writing – original draft, Writing- Reviewing and Editing. **Rongrong Li:** Methodology, Data curation, Investigation Writing – original draft, Writing- Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by National Natural Science Foundation of China (Grant No. 71934007, 72104246).

References

- [1] WHO, WHO Coronavirus Disease (COVID-19) Dashboard, World Health Organization, 2020.
- [2] Q. Wang, M. Su, M. Zhang, R. Li, Integrating digital technologies and public health to fight covid-19 pandemic: key technologies, applications, challenges and outlook of digital healthcare, *Int. J. Environ. Res. Publ. Health* 18 (2021).
- [3] IEA, Global Energy Review 2020, International Energy Agency, 2020.
- [4] C. Editorial, Coronavirus Impact on Energy Markets, 2020.
- [5] R. Madurai Elavarasan, G.M. Shafiullah, K. Raju, V. Mudgal, M.T. Arif, T. Jamal, S. Subramanian, V.S. Sriraja Balaguru, K.S. Reddy, U. Subramaniam, COVID-19: impact analysis and recommendations for power sector operation, *Appl. Energy* 279 (2020), 115739-115739.
- [6] UNEP, Global Trends in Renewable Energy Investment 2020, UN Environment Programme, 2020.
- [7] IEA, Renewables 2020, International Energy Agency, 2020.
- [8] Q. Wang, S. Li, F. Jiang, Uncovering the impact of the COVID-19 pandemic on energy consumption: new insight from difference between pandemic-free scenario and actual electricity consumption in China, *J. Clean. Prod.* 313 (2021).
- [9] J. Radtke, Smart energy systems beyond the age of COVID-19: towards a new order of monitoring, disciplining and sanctioning energy behavior? *Energy Res. Social Sci.* 84 (2022) 102355.
- [10] S.E. Hosseini, An outlook on the global development of renewable and sustainable energy at the time of COVID-19, *Energy Res. Social Sci.* 68 (2020).
- [11] R.M. Elavarasan, R. Pugazhendhi, T. Jamal, J. Dyduch, M.T. Arif, N.M. Kumar, G. M. Shafiullah, S.S. Chopra, M. Nadarajah, Envisioning the UN Sustainable Development Goals (SDGs) through the Lens of Energy Sustainability (SDG 7) in the Post-COVID-19 World, *APPLIED ENERGY*, 2021, p. 292.
- [12] M.M. Akrofi, S.H. Antwi, COVID-19 Energy Sector Responses in Africa: A Review of Preliminary Government Interventions, vol. 68, ENERGY RESEARCH & SOCIAL SCIENCE, 2020.
- [13] A. Naderipour, Z. Abdul-Malek, N.A. Ahmad, H. Kamyab, V. Ashokkumar, C. Ngamcharussrivichai, S. Chelliapan, Effect of COVID-19 Virus on Reducing GHG Emission and Increasing Energy Generated by Renewable Energy Sources: A Brief Study in Malaysian Context, ENVIRONMENTAL TECHNOLOGY & INNOVATION, 2020, p. 20.
- [14] J. Gosens, F. Jotzo, China's post-COVID-19 stimulus: No Green New Deal in sight, *Environ. Innov. Soc. Transit.* 36 (2020) 250–254.
- [15] D. Pamucar, M. Devcic, F. Canitez, T. Paksoy, V. Lukovac, A novel methodology for prioritizing zero-carbon measures for sustainable transport, *Sustain. Prod. Consum.* 27 (2021) 1093–1112.
- [16] D. Wan, R. Xue, M. Linnenluecke, J. Tian, Y. Shan, The impact of investor attention during COVID-19 on investment in clean energy versus fossil fuel firms, *Finance Res. Lett.* 43 (2021).
- [17] D. Chiaramonti, G. Talluri, N. Scarlat, M. Prussi, The Challenge of Forecasting the Role of Biofuel in EU Transport Decarbonisation at 2050: A Meta-Analysis Review of Published Scenarios, vol. 139, RENEWABLE & SUSTAINABLE ENERGY REVIEWS, 2021.
- [18] B. Kitchenham, O.P. Brereton, D. Budgen, M. Turner, J. Bailey, S.J.I. Linkman, S. Technology, Systematic literature reviews in software engineering-A systematic literature review 51 (2009) 7–15.
- [19] D.C.D. Freitas, L.G.D. Oliveira, R.L.C.A.J. Gesto, Produeo, A Theoretical Framework to Adopt Collaborative Initiatives in Supply Chains, 2019, p. 26.
- [20] C.-w. Shen, J.-t. Ho, Technology-enhanced learning in higher education: a bibliometric analysis with latent semantic approach, *Comput. Hum. Behav.* 104 (2020).
- [21] D. Valdez, A.C. Pickett, P. Goodson, Topic modeling: latent semantic analysis for the social sciences, *Soc. Sci. Q.* 99 (2018) 1665–1679.
- [22] H. Kwon, J. Kim, Y. Park, Applying LSA text mining technique in envisioning social impacts of emerging technologies: the case of drone technology, *Technovation* 60–61 (2017) 15–28.
- [23] D. Liu, M. Liu, X. Xu, J. Wang, C. Fan, X. Li, J. Han, Future prospects research on offshore wind power scale in China based on signal decomposition and extreme learning machine optimized by principal component analysis, *Energy Sci. Eng.* 8 (2020) 3514–3530.
- [24] A. Alagumalai, O. Mahian, M. Aghbashlo, M. Tabatabaei, S. Wongwises, Z. L. Wang, Towards smart cities powered by nanogenerators: bibliometric and machine learning-based analysis, *Nano Energy* 83 (2021).
- [25] J.A. Teixeira da Silva, P. Tsigaris, M. Erfanmanesh, Publishing volumes in major databases related to Covid-19, *Scientometrics* 126 (2021) 831–842.
- [26] J. Nowakowska, J. Sobocińska, M. Lewicki, Z. Lemanska, P. Rzymski, When Science Goes Viral: the Research Response during Three Months of the COVID-19 Outbreak, vol. 129, BIOMEDICINE & PHARMACOTHERAPY, 2020.
- [27] S. Aviv-Reuven, A. Rosenfeld, Publication patterns' changes due to the COVID-19 pandemic: a longitudinal and short-term scientometric analysis, *Scientometrics* 126 (2021) 6761–6784.
- [28] A. Sharif, C. Aloui, Ljssep. Yarovaya, COVID-19 Pandemic, Oil Prices, Stock Market, Geopolitical Risk and Policy Uncertainty Nexus in the US Economy: Fresh Evidence from the Wavelet-Based Approach.
- [29] J.C. Reboredo, M.A. Rivera-Castro, A.J.E.E. Ugolini, Wavelet-based Test of Co-movement and Causality between Oil and Renewable Energy Stock Prices, 2016, p. 61.
- [30] B. Awartani, H.J.E. Abdo, The Co-movement between Oil and Clean Energy Stocks: A Wavelet-Based Analysis of Horizon Associations, 2019.
- [31] M. Nicola, Z. Alsafi, C. Sohrabi, A. Kerwan, Rijos. Agha, The Socio-Economic Implications of the Coronavirus and COVID-19 Pandemic: A Review, 2020, p. 78.
- [32] M.C. Collivignarelli, A. Abbà, G. Bertanza, R. Pedrazzani, M. Majsotte, Miino, Lockdown for COVID-2019 in Milan: what Are the Effects on Air Quality?, vol. 732, 2020, p. 139280.
- [33] M.A. Zambrano-Monserrate, M. Alejandra Ruano, L. Sanchez-Alcalde, Indirect Effects of COVID-19 on the Environment, *Science of the Total Environment*, 2020, p. 728.
- [34] P. Lal, A. Kumar, S. Kumar, S. Kumari, P. Saikia, A. Dayanandan, D. Adhikari, M. L. Khan, The Dark Cloud with a Silver Lining: Assessing the Impact of the SARS COVID-19 Pandemic on the Global Environment, *Science of the Total Environment*, 2020, p. 732.
- [35] C. Le Quéré, R.B. Jackson, M.W. Jones, A.J.P. Smith, S. Abernethy, R.M. Andrew, A.J. De-Gol, D.R. Willis, Y. Shan, J.G. Canadell, P. Friedlingstein, F. Creutzig, G. P. Peters, Temporary reduction in daily global CO₂ emissions during the COVID-19 forced confinement, *Nat. Clim. Change* 10 (2020) 647–653.
- [36] A. Tobías, C. Carnerero, C. Reche, J. Massagué, M. Via, M.C. Minguillón, A. Alastuey, X. Querol, Changes in Air Quality during the Lockdown in Barcelona (Spain) One Month into the SARS-CoV-2 Epidemic, *Science of the Total Environment*, 2020, p. 726.
- [37] B.K. Sovacool, D. Furszyfer Del Rio, S. Griffiths, Contextualizing the Covid-19 pandemic for a carbon-constrained world: insights for sustainability transitions, energy justice, and research methodology, *Energy Res. Social Sci.* 68 (2020).
- [38] A.D. Bank, Southeast Asia Can Use a COVID-19 Recovery to Become Global Sustainable Energy Hub, 2020.
- [39] South SEforAll, Asia Should Prioritize Sustainable Energy to Address Energy Access Gaps and Accelerate Economic Recovery, Sustainable Energy for All, 2020.
- [40] G.T. Tucho, D.M. Kumsa, Challenges of achieving sustainable development goal 7 from the perspectives of access to modern cooking energy in developing countries, *Front. Energy Res.* 8 (2020).
- [41] S. Pradhan, D. Ghose, Shabbiruddin, Present and Future Impact of COVID-19 in the Renewable Energy Sector: a Case Study on India, Energy Sources Part A- Recovery Utilization and Environmental Effects, 2020.
- [42] SEforALL, SEforALL Analysis of SDG7 Progress - 2020, Sustainable Energy for All, 2020.
- [43] Q. Wang, R. Huang, The impact of COVID-19 pandemic on sustainable development goals – a survey, *Environ. Res.* 202 (2021) 111637.
- [44] R. Zhang, Y. Zhang, H. Lin, X. Feng, T.-M. Fu, Y. Wang, NO_x emission reduction and recovery during COVID-19 in East China, *Atmosphere* (2020) 11.
- [45] Q. Wang, S. Wang, X.-t. Jiang, Preventing a rebound in carbon intensity post-COVID-19 – lessons learned from the change in carbon intensity before and after the 2008 financial crisis, *Sustain. Prod. Consum.* 27 (2021) 1841–1856.
- [46] Q. Wang, Sjeotte. Wang, Preventing Carbon Emission Retaliatory Rebound Post-COVID-19 Requires Expanding Free Trade and Improving Energy Efficiency, vol. 746, 2020, p. 141158.
- [47] R. Huang, L.J.A.E. Tian, CO₂ emissions inequality through the lens of developing countries 281 (2021) 116043.
- [48] World Resources Institute, Building a 100 Percent Clean Economy: Opportunities for an Equitable, Low-Carbon Recovery, 2020.
- [49] IEA, Annual Change in Global Energy-Related CO₂ Emissions, 1900–2020, International Energy Agency, Paris, 2020. IEA.
- [50] B. Lahcen, J. Brusselaers, K. Vrancken, Y. Dams, C. Da Silva Paes, J. Eyckmans, S. Rousseau, Green recovery policies for the COVID-19 crisis: modelling the impact on the economy and greenhouse gas emissions, *Environ. Resour. Econ.* 76 (2020) 731–750.
- [51] Q. Wang, S. Li, R. Li, F. Jiang, Underestimated impact of the COVID-19 on carbon emission reduction in developing countries – a novel assessment based on scenario analysis, *Environ. Res.* 204 (2022) 111990.
- [52] IEA, Fuel report Renewables (2020) 2020.

- [53] L. Jiang, L. Yu, B. Xue, X. Chen, Z. Mi, Who is energy poor? Evidence from the least developed regions in China, *Energy Pol.* 137 (2020).
- [54] A.P. Heynen, P.A. Lant, S. Smart, S. Sridharan, C. Greig, Off-grid opportunities and threats in the wake of India's electrification push, *Energy, Sustainability and Society* 9 (2019).
- [55] Rocky Mountain Institute, Powering Health across Africa through COVID-19 and a Changing Climate, 2020.
- [56] World Resources Institute, Solar Power: A Rural Indian Hospital's Key to Fighting COVID-19, 2020.
- [57] M.G. Gebreslassie, COVID-19 and energy access: an opportunity or a challenge for the African continent? *Energy Res. Social Sci.* 68 (2020).
- [58] D. Carmon, A. Navon, R. MacHlev, J. Belikov, Y. Levron, Readiness of small energy markets and electric power grids to global health crises: lessons from the COVID-19 pandemic, *IEEE Access* 8 (2020) 127234–127243.
- [59] S. Baurzhan, G.P. Jenkins, Off-grid solar PV: is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries? *Renew. Sustain. Energy Rev.* 60 (2016) 1405–1418.
- [60] R. Zaman, O. van Vliet, A. Posch, Energy access and pandemic-resilient livelihoods: the role of solar energy safety nets, *Energy Res. Social Sci.* 71 (2021).
- [61] N.A. Alwan, R.A. Burgess, S. Ashworth, R. Beale, N. Bhadelia, D. Bogaert, J. Dowd, I. Eckerle, L.R. Goldman, T. Greenhalgh, D. Gurdasani, A. Hamdy, W. P. Hanage, E.B. Hodcroft, Z. Hyde, P. Kellam, M. Kelly-Irving, F. Krammer, M. Lipsitch, A. McNally, M. McKee, A. Nouri, D. Pimenta, V. Priesemann, H. Rutter, J. Silver, D. Sridhar, C. Swanton, R.P. Walensky, G. Yamey, H. Ziauddine, Scientific consensus on the COVID-19 pandemic: we need to act now, *Lancet* 396 (2020) E71–E72.
- [62] M.J.S. Coccia, How (Un)sustainable environments are related to the diffusion of COVID-19: the relation between coronavirus disease 2019, Air Pollution, Wind Resource and Energy 12 (2020) 1–12.
- [63] A. Frontera, C. Martin, K. Vlachos, G.J.J.o.I. Sgubin, Regional Air Pollution Persistence Links to COVID-19 Infection Zoning, 2020, p. 81.
- [64] A. Ferrannini, E. Barbieri, M. Biggeri, M. Mrdjwd. Tommaso, Industrial policy for sustainable human development in the post-Covid19 era 137 (2021) 105215.
- [65] IEA, Offshore Wind, International Energy Agency, 2020.
- [66] C. Li, X. Ma, T. Fu, S. Guan, Does Public Concern over Haze Pollution Matter? Evidence from Beijing-Tianjin-Hebei Region, *Science of the Total Environment*, China, 2021, p. 755.
- [67] H. Rozehnalová, M. Mádr, L. Formanová, B.A.J.P. Ekorozwoju, Influence of pollutants from Transport on Life Expectancy in the EU Countries 16 (2020) 209–217.
- [68] A. Czaplicka-Kotas, J. Kulczycka, N.J.S. Iwaszcuk, Energy Clusters as a New Urban Symbiosis Concept for Increasing Renewable Energy Production—A Case Study of Zakopane City, vol. 12, 2020.
- [69] I.M. Peters, C. Brabec, T. Buonassisi, J. Hauch, A.M. Nobre, The impact of COVID-19-related measures on the solar resource in areas with high levels of air pollution, *Joule* 4 (2020) 1681–1687.
- [70] I. D'Adamo, M. Gastaldi, P. Morone, The post COVID-19 green recovery in practice: assessing the profitability of a policy proposal on residential photovoltaic plants, *Energy Pol.* 147 (2020).
- [71] J.A. Rehbein, J.E.M. Watson, J.L. Lane, L.J. Sonter, O. Venter, S.C. Atkinson, J. R. Allan, Renewable energy development threatens many globally important biodiversity areas, *Global Change Biol.* 26 (2020) 3040–3051.
- [72] K. Solaun, E. Cerdá, Climate change impacts on renewable energy generation. A review of quantitative projections, *Renew. Sustain. Energy Rev.* 116 (2019).
- [73] A.F.P. de Lucena, A.S. Szkllo, R. Schaeffer, R.R. de Souza, B.S.M.C. Borba, I.V.L. da Costa, A.O.P. Júnior, S.H.F. da Cunha, The vulnerability of renewable energy to climate change in Brazil, *Energy Pol.* 37 (2009) 879–889.
- [74] IRENA, IRENA and African Development Bank Partner to Scale up Renewables Investments in Africa Tweet, 2020.
- [75] E.B. Barbier, J.C. Burgess, Sustainability and Development after COVID-19, vol. 135, *World Dev.*, 2020.
- [76] C. Kuzemko, M. Bradshaw, G. Bridge, A. Goldthau, J. Jewell, I. Overland, D. Scholten, T. Van de Graaf, K. Westphal, Covid-19 and the politics of sustainable energy transitions, *Energy Res. Social Sci.* 68 (2020).
- [77] N. Yoshino, F. Taghizadeh-Hesary, M. Otsuka, Covid-19 and optimal portfolio selection for investment in sustainable development goals, *Finance Res. Lett.* 38 (2021).
- [78] M.M. Akrofi, S.H. Antwi, COVID-19 energy sector responses in Africa: a review of preliminary government interventions, *Energy Res. Social Sci.* 68 (2020).
- [79] E.B. Barbier, Greening the post-pandemic recovery in the G20, *Environ. Resour. Econ.* 76 (2020) 685–703.
- [80] B. Steffen, F. Egli, M. Pahle, T.S. Schmidt, Navigating the clean energy transition in the COVID-19 crisis, *Joule* 4 (2020) 1137–1141.
- [81] S. Corbet, J.W. Goodell, S. Güney, Co-movements and Spillovers of Oil and Renewable Firms under Extreme Conditions: New Evidence from Negative WTI Prices during COVID-19, *Energy Econ.* 2020, p. 92.
- [82] Q. Wang, F. Zhang, What does the China's economic recovery after COVID-19 pandemic mean for the economic growth and energy consumption of other countries? *J. Clean. Prod.* 295 (2021) 126265.
- [83] M. Andrijevic, C.F. Schleussner, M.J. Gidden, D.L. McCollum, J. Rogelj, COVID-19 recovery funds dwarf clean energy investment needs, *Science* 370 (2020) 298–300.
- [84] E. Ghiani, M. Galici, M. Mureddu, F. Pilo, Impact on electricity consumption and market pricing of energy and ancillary services during pandemic of COVID-19 in Italy, *Energies* 13 (2020).
- [85] I. Santiago, A. Moreno-Munoz, P. Quintero-Jiménez, F. Garcia-Torres, M. J. Gonzalez-Redondo, Electricity demand during pandemic times: the case of the COVID-19 in Spain, *Energy Pol.* 148 (2021).
- [86] H. Zhong, Z. Tan, Y. He, L. Xie, C. Kang, Implications of COVID-19 for the electricity industry: a comprehensive review, *CSEE J. Power Energy Syst.* 6 (2020) 489–495.
- [87] A. Werth, P. Gravino, G. Prevedello, Impact Analysis of COVID-19 Responses on Energy Grid Dynamics in Europe, *Applied Energy*, 2021, p. 281.
- [88] A. Naderipour, Z. Abdul-Malek, N.A. Ahmad, H. Kamyab, V. Ashokkumar, C. Ngamcharussivichai, S. Chelliapan, Effect of COVID-19 Virus on Reducing GHG Emission and Increasing Energy Generated by Renewable Energy Sources: A Brief Study in Malaysian Context, *Environmental Technology and Innovation*, 2020, p. 20.
- [89] K.T. Gillingham, C.R. Knittel, J. Li, M. Ovaere, M. Reguant, The short-run and long-run effects of covid-19 on energy and the environment, *Joule* 4 (2020) 1337–1341.
- [90] M.F. Bashir, B. Ma, L. Shahzad, A brief review of socio-economic and environmental impact of Covid-19, *Air Quality, Atmosphere and Health* 13 (2020) 1403–1409.
- [91] H. Eroğlu, Effects of Covid-19 outbreak on environment and renewable energy sector, *Environ. Dev. Sustain.* 23 (2021) 4782–4790.
- [92] M. Coccia, How (Un)sustainable environments are related to the diffusion of covid-19: the relation between coronavirus disease 2019, air pollution, wind resource and energy, *Sustainability* 12 (2020) 1–12.
- [93] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, F. Herrera, An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the Fuzzy Sets Theory field, *Journal of Informetrics* 5 (2011) 146–166.
- [94] M. Callon, J.P. Courtial, F. Laville, Co-word analysis as a tool for describing the network of interactions between basic and technological research: the case of polymer chemistry, *Scientometrics* 22 (1991) 155–205.
- [95] UNEP, Falling Clean Energy Costs Provide Opportunity to Boost Climate Action in COVID-19 Recovery Packages, 2020.
- [96] Global Perspective Human Stories, First Person: Supporting Migrants on the COVID-19 Frontline in Myanmar, 2020.
- [97] R. Ulewicz, D. Siwiec, A. Pacana, M. Tutak, J. Brodny, Multi-criteria method for the selection of renewable energy sources in the polish industrial sector, *Energies* 14 (2021) 2386.
- [98] S.A.R. Khan, Z. Yu, H. Golpira, A. Sharif, A. Mardani, A state-of-the-art review and meta-analysis on sustainable supply chain management: future research directions, *J. Clean. Prod.* 278 (2021) 123357.
- [99] J. Brodny, M. Tutak, P. Bindzar, Assessing the level of renewable energy development in the European union member states. A 10-year perspective, *Energies* 14 (2021).
- [100] J. Markard, D. Rosenbloom, A tale of two crises: COVID-19 and climate, *Sustain. Sci. Pract. Pol.* 16 (2020) 53–60.
- [101] Q. Wang, S. Li, M. Zhang, R. Li, Impact of COVID-19 pandemic on oil consumption in the United States: a new estimation approach, *Energy* 239 (2022) 122280.
- [102] F. Li, Z. Song, W. Liu, China's energy consumption under the global economic crisis: decomposition and sectoral analysis, *Energy Pol.* 64 (2014) 193–202.
- [103] C.T. Chong, Y.V. Fan, C.T. Lee, J.J. Klemes, Post COVID-19 ENERGY Sustainability and Carbon Emissions Neutrality, *ENERGY*, 2022, p. 241.
- [104] H. Anh Tuan, S. Nizetic, A.I. Olcer, H.C. Ong, W.-H. Chen, C.T. Chong, S. Thomas, S.A. Bandh, N. Xuan Phuong, Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: opportunities, challenges, and policy implications, *Energy Pol.* 154 (2021).
- [105] O. Anne, V. Burskyte, Z. Stasiškiene, A. Balciunas, The influence of the environmental management system on the environmental impact of seaport companies during an economic crisis: Lithuanian case study, *Environ. Sci. Pollut. Control Ser.* 22 (2015) 1072–1084.
- [106] O.H.M.N. Bashar, O.K.M.R. Bashar, Resource abundance, financial crisis and economic growth: did resource-rich countries fare better during the global financial crisis? *Aust. J. Agric. Resour. Econ.* 64 (2020) 376–395.
- [107] R. Li, Q. Wang, X. Wang, Y. Zhou, X. Han, Y. Liu, Germany's contribution to global carbon reduction might be underestimated – a new assessment based on scenario analysis with and without trade, *Technol. Forecast. Soc. Change* 176 (2022) 121465.
- [108] D. Thorpe, How investing in the green economy is the best way to post-Covid-19 economic recovery, *Proceedings of the Institution of Civil Engineers-Civil Engineering* 173 (2020), 100–100.
- [109] L. Mundaca, L. Neij, A. Markandya, P. Hennicke, J. Yan, Towards a Green Energy Economy? Assessing policy choices, strategies and transitional pathways, *Appl. Energy* 179 (2016) 1283–1292.
- [110] D. Zhang, M. Mohsin, A.K. Rasheed, Y. Chang, F. Taghizadeh-Hesary, Public spending and green economic growth in BRI region: mediating role of green finance, *Energy Pol.* 153 (2021).
- [111] M. Mohsin, H.W. Kamran, M.A. Nawaz, M.S. Hussain, A.S. Dahri, Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies, *J. Environ. Manag.* (2021) 284.
- [112] L. De la Pena, R. Guo, X. Cao, X. Ni, W. Zhang, Accelerating the energy transition to achieve carbon neutrality, *Resour. Conserv. Recycl.* (2022) 177.