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COVID-19 and energy: Influence mechanisms and research methodologies

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ABSTRACT

Considering the important role of energy in modern society, it is imperative to study the current situation and future development of energy under the influence of COVID-19. This paper identifies the current research hotspots, proposes future research directions accordingly, and summarizes the methodologies via a bibliometric analysis. Five research hotspots include COVID-19 and the changes of energy consumption, COVID-19 and the fluctuation of the energy market, COVID-19 and the development of renewable energy, COVID-19 and climate impacts caused by energy consumption, and COVID-19 and the energy policy. According to the influence mechanism of COVID-19 on each hotspot, the pandemic has exerted short-term influences on energy consumption, energy price, and air pollution. Meanwhile, the pandemic could have a far-reaching impact on the renewable energy sector, climate, and energy policy. In addition, the main methodologies are reviewed, revealing that regression analysis and scenario analysis are commonly used as the quantitative and qualitative methods, respectively. Moreover, given the nonlinear relations between the pandemic and energy, an artificial neural networks model is used to enhance the prediction efficiency of energy demand and price. Finally, policy implications for obtaining clean, low-carbon, safe, and efficient energy in the context of COVID-19 are proposed.

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1. Introduction

The outbreak of the novel coronavirus disease 2019 (COVID-19) has exerted profound and extensive influences on the global economy, society, and environment (Klemeš et al., 2020; Tahir and Ba too, 2020). As an essential pillar industry, the energy sector is extremely sensitive to external shocks like the COVID-19 pandemic for its various relations with business, industry and transportation sectors (Hosseini, 2020; Lin and Su, 2020). Therefore, energy system has been affected by the pandemic in many different aspects through different influence mechanisms. Initially, the lockdown policy during the pandemic restricted production, transport and trade both domestically and globally, directly cutting down energy demand (Yaya et al., 2020; Norouzi et al., 2020). Meanwhile, with the transformations in work modality and lifestyle caused by the lockdown policy, domestic life and online activities like E-work and E-school not only increased the electricity consumption of residential sector but also changed consumption patterns to some extent (Gu et al., 2020; Ghiani et al., 2020). In addition, COVID-19 also disturbed the equilibrium of energy market, mainly reflected in the price fluctuation of energy products and energy stocks (Connolly et al., 2020; He et al., 2020; Rostan and Rostan, 2020). COVID-19 has brought challenges for governments as well. Responding to COVID-19, governments have poured out fiscal expenditures and subsidies to combat surging infections and support residential livelihood, inducing a fiscal dilemma for many governments, especially in developing countries (Khalid et al., 2020). Therefore, some countries turned to feasible energy policies to guarantee energy security and mitigate energy poverty during the pandemic (Barbier, 2020; Sobieralski and Hubbard, 2020).

Conversely, the pandemic has also brought some dividends to the environment and climate. The reduction in energy consumption during the pandemic directly decreased the emissions of air pollutants such as NOx, SO\textsubscript{2}, CO, PM\textsubscript{2.5}, and PM\textsubscript{10}, resulting in an improvement of air quality (Balsalobre-Lorente et al., 2020; Chakraborty et al., 2020; Kerimray et al., 2020; Liu et al., 2020a). Furthermore, in terms of temperature changes, the emission re-
duction of greenhouse gas and short-lived air pollutants (NO2 and SO2) may have a cooling and warming effect on the climate, respectively (Forster et al., 2020). In short, the COVID-19 pandemic could cause an upgrading of air quality and slight mitigation of global warming in the short term.

According to the existing studies, researchers have assessed the impacts of COVID-19 on energy from many perspectives, but lacking a comprehensive assessment of the overall pandemic influences on energy. To fill this gap, this research employed bibliometric analysis to achieve the following objectives: (1) to identify the research hotspots about the impacts of COVID-19 on energy and summarize the influence mechanisms, (2) to provide new research directions according to the existing researches, (3) to summarize the main approaches applied in quantifying the impacts of COVID-19 on energy, and (4) to put forward theoretical and practical implications for the researchers and policymakers.

This study aims to provide a systematic review of the impacts of COVID-19 on energy. The contributions can be identified in three aspects. First, the bibliometric-based review identifies five research hotspots and explores the influence mechanism within each hotspot. Second, the future research trends on COVID-19 and energy are highlighted to advance the knowledge in this area. Third, the main approaches applied in quantifying and defining the impacts of COVID-19 on energy are refined.

This paper is structured as follows. Section 2 presents the methodology. Based on bibliometric analysis, the research hotspots, future research, and research methodologies are analyzed in Section 3. According to the findings, Section 4 draws conclusions and puts forward some implications.

2. Methods

2.1. Systematic literature review (SLR)

To provide a comprehensive assessment of the impacts of COVID-19 on energy, this study reviewed the related articles sourced from the Web of Science Core Collection database by a systematic literature review. According to Mulrow (1994), the main advantages of SLR method were highlighted. On the one hand, through the compression and integration of massive information, SLR is an efficient scientific method with less time consumed compared with conducting a new research. On the other hand, by generalizing and grouping similar research results from different resources, SLR can improve the statistical power and result precision in quantitative assessment and help explaining data inconsistency and contradictory findings in a given field. Referring to the research pattern of SLR, we built the overarching research framework applied in this study, which includes five major stages (seen in Fig. 1).

2.2. Step-by-step approach

As demonstrated in Fig. 1, at the onset of the review, we identified the specific questions to explore through the SLR process:

1. What aspects of energy have been influenced by the COVID-19 pandemic?
2. What are the influence mechanisms in each research hotspot?
3. What are the future research directions in each hotspot?
4. What are the main research methodologies used in the topic?

Based on the proposed questions, we conducted the literature research following the Preferred Reporting Items for Systematic reviews and Meta-Analyses Statement (PRISMA Statement). We retrieved relevant articles in the Web of Science databases with the specific search function, which limited the language and document type as “English” and “Article”, respectively. Moreover, the search function covered extensive keywords related to COVID-19 and energy, as shown in Table 1. We performed the initial search on September 13, 2020, obtaining 361 studies published from January 2020 to September 2020.

However, some retrieved articles were not closely related to the topic. To gather useful data, we combined machine screening and manual selection to guarantee the quality of the data in this research. Through an artificial refinement of research areas in the Web of Science, we excluded unrelated research fields such as medicine and biology. Then, a manual screening of title, keywords, and abstract were adopted to obtain qualified researches. Finally,
59 studies were chosen for the final reviewing scope. After deciding on the selected articles, we directly downloaded the basic information of the articles from the Web of Science platform, including author, title, keywords, and references for the data analysis, synthesis, and interpretation.

To identify the mainstream research hotspots in COVID-19 and energy, we read through the titles and abstracts to roughly classify the reviewed articles, combined with the co-occurrence analysis, which can reflect the relations among the selected articles. However, limited by the short time interval of collecting articles, there are only a few keywords with co-occurrence relations, bringing difficulties in analyzing the results. Therefore, we also conducted a co-occurrence analysis of title words to draw a more accurate classification result. The specific procedure of co-occurrence analysis for both keywords and title words is as follow. We initially made a frequency statistic of extracted keywords and title words and conducted the co-occurrence analysis after deleting the synonymous words using BibExcel. Then, we imported the processed data into the software Pajek and built a co-word network with frequencies to explore the relations among selected articles. Within the co-word network, some close-related words were classified into a certain cluster. Furthermore, considering some words are difficult to classify merely by the co-occurrence analysis, a manual partition according to more details of these articles is necessary to revise the classification results. Finally, we imported the raw picture generated in Pajek to VOSviewer software to visualize the identified thematic clusters more aesthetically. To enrich the classification results, we also conducted a co-citation analysis to point out several articles that have been cited frequently by other researchers. The basic method of co-citation analysis is similar to co-occurrence analysis, except for some details of data processing in BibExcel.

In the last step, based on a thorough reading of the full text, we presented the results of SLR from the perspectives of the influence mechanisms, future research directions, and main research methodologies, respectively, which are presented in detail in the next section.

3. Results and discussion

3.1. Research hotspots and influence mechanisms

By combining machine classification including co-occurrence analysis and co-citation analysis and thorough study of the selected 59 articles, we summarized five hotspots in Fig. 2 and Fig. 3, which presented the co-occurrence network among keywords and title words, respectively. Moreover, according to the co-citation analysis in Fig. 4, researches from Le Quére et al. (2020) and Dieter Helm (2020) were cited by 7 and 6 times respectively, which discussed the environment outcomes of the lockdown policy during the pandemic through the altered energy demand patterns around the world. More details of the articles in each hotspot are presented in Table 2.

### 3.1.1. COVID-19 and the changes in energy consumption

Since the outbreak of COVID-19, the skyrocketing infection rate has restricted around 30% of the global population from outdoor activities, which severely affected the energy consumption in different areas, including business, industries, tourism, manufacturing, transportation, tertiary, and the residential sector (Ghiani et al., 2020; Norouzi et al., 2020). However, the pandemic influences on energy consumption vary among different economic sectors. As presented in Fig. 5, we consider this problem from the sector, activity, and energy-type perspectives.

AFFECTED BY THE PANDEMIC, GROUND AND AIR TRANSPORT HAS BEEN EXTREMELY LIMITED, WHICH REDUCES ENERGY CONSUMPTION IN THE TRANSPORTATION SECTOR, SUCH AS THE AIRPLANE FUELS AND MOTOR GASOLINE. ACCORDING TO NIŽETIĆ (2020), THE NUMBER OF FLIGHTS IN EUROPE DECLINED MORE THAN 89%, WHICH DIRECTLY CUT DOWN THE CONSUMPTION OF AIRPLANE FUEL. ADDITIONALLY, OU ET AL. (2020) FOUND THAT ALL TRAVELS BY ROAD IN MARCH 2020 DECREASED BY 18.6% COMPARED TO 2019, WHICH RESULTED IN A REDUCTION OF MOTOR GASOLINE DEMAND IN THE US. FURTHERMORE, THE US GASOLINE DEMAND WAS ESTIMATED TO EXPERIENCE SLOGGED GROWTH AFTER A Quick rebound in May, but it was unlikely to fully recover prior to October 2020 under the pessimistic scenario of current infection and lockdown policy (Ou et al., 2020). To conclude, the energy consumption in the transportation sector was severely affected by the COVID-19 due to a sharp decline in vehicle and airplane travel.

Among the various energy, electricity is widely used in both households and industries, thus regarded as the fundamental criteria of economic activity (Agdas and Barooha, 2020). Therefore, the variations in electricity usage during the pandemic have profoundly intrigued researchers. Some studies quantitatively estimated the negative impact of COVID-19 on electricity consumption especially in countries such as China, US, and India, which are the top three consumers of electricity, accounting for nearly 28%, 17%, and 5% of global electricity consumption, respectively (Jannat, 2020; Elavarasan, 2020). The reductions in electricity consumption were caused by the pandemic directly and indirectly. On the one hand, the shutdown of the industry sector directly led to the reduction in the total amount of electricity consumption. On the other hand, the lockdown policies restricted some social activities in night, weekend and holiday, such as eating out and entertainment activities, which indirectly induced a decline in electricity consumption (Fezzi and Fanghella, 2020).

Moreover, the COVID-19 not only affected the total amount of electricity consumption in industry and service sectors but also changed the consumption patterns in the residential sector (Norouzi et al., 2020; Rouleau and Gosselin, 2021). According to Rouleau and Gosselin (2021), except for the slight increase in overall residential electricity consumption, the electricity consumption

### Table 1

| Retrieval Type | Content |
|---------------|---------|
| Formula       | TS= (“Coronavirus disease 2019” OR “COVID-19” OR “Novel Coronavirus” OR “Sars-Cov-2”) AND TS= (“energy” OR “fuel” OR “oil” OR “coal” OR “petroleum” OR “natural gas” OR “fossil fuel” OR “wind” OR “solar” OR “nuclear” OR “hydropower” OR “hydroelectricity” OR “biogas” OR “bio” energy” OR “renewable energy” OR “alternative energy” OR “electricity”) |
| Language      | English |
| Document type | Article |
| Index         | SCI-EXPANDED, SSCI |
| Year          | 2020    |
Table 2
Research hotspots of COVID-19 and energy.

| Author(s) | Purpose(s) | Sample | Key findings |
|-----------|-------------|--------|--------------|
| Cluster 1: COVID-19 and the changes of energy consumption (11) |
| Ou et al. (2020) | To project the impact of COVID-19 on US medium-term motor gasoline demand in different scenarios of pandemic development by using machine-learning-based model | US | Under the current pandemic scenario, the growth of motor gasoline demand is slow and is unlikely to reach previous level in the medium term. Under the optimistic pandemic scenario, the motor gasoline demand is expected to continue growing and recover to about 98% of the normal demand by late September 2020. Under the pessimistic scenario, the second wave of infections in mid-June to August 2020 could substantially lower the gasoline demand again. |
| Jannat (2020) | To explore the effects of COVID-19 on Indian Energy Consumption | India | The lockdown policy positively influenced the energy consumption. Regions with higher income levels were more likely to recover their energy, consumption to pre-crisis levels faster than those with lower income levels. |
| Gu et al. (2020) | To explore how enterprises in Suzhou respond to COVID-19 by analyzing their electricity consumption | Suzhou | At the aggregate level, firms’ electricity consumption dropped by an average of 57%. Manufacturing firms were adversely affected, while industries such as information, computer services, and health care had a positive response to the COVID-19 shock. |
| Fezzi and Fanghella (2020) | To estimate the short-run impacts of COVID-19 on the economy provide information for shaping future lockdown policy | Italy | The relationship between electricity load change (excluding residential users) and GDP change is satisfactory in the very short-run at the national level. |
| Cluster 2: COVID-19 and the fluctuation of energy market (13) |
| Šiřáčik et al. (2020) | To explore the impact of COVID-19 on the financial movement of Crude Oil price and three US stock indexes | Global | The market is gradually adjusting oil prices due to the fact of joint agreement on production cuts. The gradual opening of markets and recovery of demand and the improvement of relations between oil exporters will contribute to the temporary market stability. |
| Author(s) | Purpose(s) | Sample | Key findings |
| Connolly et al. (2020) | To explain the relationship between the decline in oil prices and tectonic shifts in global energy markets caused by pandemic and Russian –an economy is dependent on oil and gas sales as the primary source of growth | Russia | Any prolonged slump in oil and gas revenues could threaten the Russian economy. In the course of the crisis, much of the responsibility for handling the pandemic has been devolved to the regions. |
| Sharif et al. (2020) | To analyze the nexus between the recent spread of COVID-19, oil price volatility, stock market, geopolitical risk and economic policy | US | The oil slump had the strongest impact on the US stock markets in comparison to both COVID-19, EPU and GPR. COVID-19 pandemic can influence the oil prices, which can be explained by imposed travel restrictions. |
| Cluster 3: COVID-19 and the development of renewable energy (11) |
| Zimon et al. (2020) | To examine if the merge into industry purchasing groups is financially safer for SMEs in renewable energy sector during pandemic | Poland | Increasing the efficiency of individual entities of the renewable energy industry within purchasing groups becomes particularly important during pandemic. Bio-energy production is a part of farm diversification dealing with the Covid-19 crisis. |
| Mastronardi et al. (2020) | To investigate the reactions of Italian farms to COVID-19 | Italy | The pyrolysis of the PPE kit can be done in a closed thermal reactor, which will convert the polypropylene into liquid fuels. The liquid fuel produced from plastics is clean and have fuel properties similar to fossil fuels. |
| Jain et al. (2020) | To introduce and explain the strategy for the repurposing of coronavirus-related biomedical waste (personal protection equipment kits) by production of biofuel | India | The direct pandemic-driven climate response will be negligible, with a cooling of around 0.01 ± 0.005°C by 2030 compared to a baseline scenario. COVID-19 measures substantially decrease carbon emissions due to nationwide industry lockdown. There’s a reduction in some atmospheric pollutants (PM, SO2, CO, NO2). There’s an unexpected increase in SO2 in the rural areas and O3 in both urban and rural areas. |
| Author(s) | Purpose(s) | Sample | Key findings |
| Cluster 4: COVID-19 and climate impacts caused by energy consumption (13) |
| Forster et al. (2020) | To investigate the climate impacts of COVID-19 | Global | The more persistent the COVID-19 shock is, the less the MSR is able to serve its purpose. |
| Clafin et al. (2020) | To analyze the impacts of COVID-19 on carbon emissions | Global | More stringent measures are needed to meet Paris agreement. |
| Anser et al. (2020) | To investigate the climate impacts of COVID-19 | Global | |
| Wang et al. (2020b) | To investigate the effects of city lockdowns on air quality | Hangzhou | |
| Cluster 5: COVID-19 and energy policy (11) |
| Gerlagh et al. (2020) | To explore whether the MSR (Market Stability Reserve) can stabilize the EU-ETS price during pandemic turbulence | Europe | |
| Meles et al. (2020) | To explore the impact of COVID-19 on the fulfillment of 2030 EU CO2 emissions target under various economic recovery scenarios after pandemic | Europe | |

(continued on next page)
occurred throughout the day instead of being concentrated in the evening as observed before the lockdown, indicating the transformation of consumption patterns. Generally speaking, the impacts of COVID-19 on electricity consumption patterns were categorized into three aspects. First, due to the lockdown policy, students and employed adults turned to electronic devices like smartphones and computers to continue schooling and working remotely at home, which led to an increase in residential electricity consumption in the daytime (Chiani et al., 2020; Krzysztofik et al., 2020). Second, the electricity consumption ramps up more slowly in the morning.
compared to the pre-pandemic circumstances because of the narrowing needs for work commute and cooking breakfast (Gu et al., 2020; Ghiani et al., 2020). Third, the peak demand in the evening remained sustained, due to some less-affected consumption activities such as preparing dinners, watching TV, and using other electric appliances for household entertainment, despite the fact that these peaks are lower than previous levels to some extent. To conclude, the temporal heterogeneity of electricity consumption pattern mainly corresponded to the variations in residents’ lifestyles and working modality during lockdown time.

COVID-19 has a significant impact on energy consumption from the perspectives of total consumption and consumption patterns. From the results of the selected articles of this hotspot, a significant decline has been observed in the consumption of all mentioned energy-types, thus supporting the negative impacts of COVID-19 on energy consumption and demand. Moreover, the majority of researchers focused on changes in electricity consumption in different sectors.

3.1.2. COVID-19 and the fluctuation of energy market

As the pandemic is steadily worsening the demand and disrupting energy supply, the energy market, especially the crude oil market, is full of uncertainties and fluctuation, attracting research interests (Aydın and Ari, 2020; Štifanić et al., 2020). According to Fig. 6, the fluctuations of the energy market can be manifested in two aspects: the volatility of energy price and energy stock price. Worse still, the fluctuation of the energy market may create a spillover effect and pose danger to the rest of the economy, especially for those main energy exporters.

Due to the overall demand reduction during the COVID-19, various energy prices experienced a slump during the pandemic. In Spain, the actual wholesale electricity price in May 2020 was 60%

Fig. 3. The co-occurrence network of title words.
lower than expected. In the case of natural gas, the price in the same month was 62% lower than expected (Abadie, 2021). Moreover, coupled with conflicts between main oil exporters in the same period, oil sales price experienced a sharper decline during the pandemic. By February 17 2020, the Brent oil price plummeted about 59% from the last crest value. Furthermore, the West Texas Intermediate oil price plunged to an unprecedented negative value in April 2020 (Ou et al., 2020; Aydin and Ari, 2020). Despite the sharp decline in oil demand, the supply maintained its prepandemic level, thus creating a glut of oil and full capacities of petroleum storage facilities in some countries for the first time in history (Bildirici et al., 2020). As a consequence, financial derivatives like crude oil futures have to be sold off when the storage capacity runs out, directly leading to a huge decline in oil prices.

The nexus between energy price especially oil price and stock returns were examined by many researchers. Prabheesh et al. (2020) found that COVID-19 strengthened the positive relationship between oil prices and stock returns in four major net oil-importing Asian countries. It implied that the signal of falling oil price during the pandemic is perceived by the stock market as a negative demand shock especially in the presence of high economic uncertainty caused by the pandemic. COVID-19 has a negative impact on company performance, especially for energy companies. The energy industry was characterized by a higher fixed assets ratio and financial leverage, which brings more fixed costs and greater operating risks than other industries (Fu and Shen, 2020). Actually, the stock value of some energy giants like Royal Dutch Shell and BP was negatively affected by COVID-19 (Gerlagh et al., 2020). Based on the energy price decline, energy stock price volatility is generated through the influence mechanism “revenue loss of energy companies–pessimistic investment sentiment-increasing volatility of energy stock price” (Lee et al., 2002). Different from some technical companies including Amazon, Netflix, and Zoom which can adopt online work modality to overcome the pandemic shock, energy-related industries like mining, electric, and heating are unable to complete their tasks only through computer (He et al., 2020). Therefore, energy enterprises suffered heavier revenue losses during the lockdown period with the significant shrinkage of stock values.

In addition, the fluctuation of the energy market may spread to other economic fields for the fundamental position of the energy industry in the macro-economy (Prabheesh et al., 2020). However, the spillover influences vary with countries for their different roles in the international energy market. For energy exporters, the fluctuation of the energy market can translate into macroeconomic pressure by deteriorating the national budgets reimbursed via large-scale production and exports of oil and gas. For instance, due to the collapse in global oil demand caused by the pandemic and the pessimistic forecast of the future revenues from the energy sector, the economy of Russia and Saudi Arabia has been adversely affected (Connolly et al., 2020; Rostan and Rostan, 2020). In contrast, for energy importers, low oil prices exerted a positive influence on the macroeconomy. In spite of a 1.16% decrease in Turkey’s GDP caused by declining export demands and revenue loss in the tourism, transport, and tertiary industries, the falling import oil price can compensate for economic downturn to some extent by lowering energy cost (Aydın and Ari, 2020). More specifically, in the scenarios of 25% and 50% falling oil prices, the decrease in GDP caused by COVID-19 may be counterbalanced by 0.72% and 1.56%, respectively (Aydın and Ari, 2020).

As a public emergency incident, COVID-19 has a profound impact on the energy market. From the micro perspective, the pandemic has diminished both energy prices and stock values of energy companies, resulting in huge fluctuation of energy market. From the macro perspective, the spillover effects of energy market volatility have affected the macroeconomy condition of both energy exporters and importers.

### 3.1.3. COVID-19 and renewable energy industry

COVID-19 has created chaos in energy system by reducing energy demand, suspending energy production and distorting energy price. Against this background, the limitation and vulnerability of the fossil fuel industry have been realized such as price volatility, high dependence on labor force and relatively rigid production mode (Graff and Carley, 2020; Malliet et al., 2020). Therefore, the renewable energy industry will grow to be more important in the future energy system, requiring a comprehensive analysis of the pandemic impacts on it. As seen in Fig. 7, we have summarized these impacts in terms of both positive and negative aspects.

As a booster, COVID-19 can stimulate the development of renewable energy industry through three aspects. First and foremost, the vulnerability of fossil fuels to external shocks can induce more investment interests in renewable energy with more stable production costs (Al-Ghussain et al., 2021). In addition, renewable energy has technical advantages compared with traditional energy in the context of COVID-19. Specifically, decentralized production technologies of renewable energy enable possible alternative energy resource when the energy supply from traditional centralized energy centers is disrupted by contingencies (Reynolds et al., 2019). Furthermore, due to their lower operating costs and regulation priority, renewables are generally dispatched before other electricity sources (IEA, 2020). Hence, the production of renewables may be more resilient and flexible when facing lower electricity demand caused by the pandemic. Actually, Werth et al. (2021) found that energy generation by coal, oil, and nuclear reduced considerably, when the share of intermittent renewable sources increased during the pandemic. Finally, the current pandemic has stimulated internal reforms of both production modes and operation modes in the renewable energy sector. Mastronardi et al. (2020) found that some farms are developing bio-energy production to diversify their production activities and make up for the losses during the pandemic. Additionally, some small and medium companies in the renewable energy industry choose to merge into industry purchasing groups
to decrease costs (Zimon et al., 2020). Such reforms can smooth the transition from the conventional fossil energy to renewable energy.

Conversely, COVID-19 also imposed some negative impacts on renewable energy industry. Most importantly, due to the lockdown policy and border closure, the disruption of global supply chains and the restriction of labor mobility severely inhibited the production and logistics of solar photovoltaic modules and wind turbine components (IEA, 2020). Hence, importer countries including India and US fail to gain raw materials and semi-finished products of solar energy and wind energy from nations such as China and East Asia, which are the main producers and exporters of these renewable energy materials (Song et al., 2020). Furthermore, since substantial relief funding was spent on society, government revenues inevitably plunged, let alone the funds supporting renewable energy. Last, the shrinkage of energy demand due to the pandemic could ultimately prevent the growth of renewable energy industry. Liquid biofuels, which are commonly blended with gasoline or diesel, has been adversely affected by declining fuel demand from road transport (IEA, 2020).

In the short term, the renewable sector encountered supply chain disruption due to the lockdown and quarantine measures, resulting in a lower growth rate of electricity generation using various renewable sources, including wind, hydropower, solar photovoltaic, and bioenergy (Jiang et al., 2021). However, in the long term, some extreme incidents happened during the pandemic may offer motivation for renewable energy producers. For example, a record of negative wholesale power prices was set under the influence of a slump in energy demand caused by pandemic and high renewable energy outputs caused by an exceptionally sunny and windy few months in Germany (Jiang et al., 2021). To avoid turning off plants, fossil generators had to pay for wholesale customers. Meanwhile, renewables generators are protected by guaranteed feed-in-tariff prices to maintain earnings during the pandemic. In light of such a phenomenon, the proportion of renewable energy is expected to be enlarged in the post-pandemic era.

3.1.4. COVID-19 and climate impacts caused by energy consumption

Beyond the consumption and production of energy, COVID-19 has influenced the environment to some extent. Therefore, the influence of the pandemic and lockdown policy on the air quality and climate will be discussed in this section. In the residential sector, the stay-at-home order caused an abrupt decline of energy consumption by restricting basic travel, vehicle movement, and entertainment activities (Sui et al., 2020). In the industry sector, due to the lockdown policy and staff shortage, the energy consumption in energy-intensive industries such as transportation, electric power, and chemical industry have been drastically restricted (Le
Quéré et al., 2020; Wang et al., 2020b). The significant reduction in fossil fuel combustion directly contributed to the diminishing emissions of greenhouse gas (GHG) and air pollutant emissions such as nitrogen dioxide (NO₂), ozone (O₃), sulfur dioxide (SO₂), carbon monoxide (CO), and particulate matters (Safarian et al., 2020; Zhang et al., 2020). Moreover, the variations of these emissions may indirectly influence the climate through both cooling and warming effects. As presented in Fig. 8, the solid and dashed lines represent the direct and indirect impacts of the emission reduction, respectively.

Due to the emission reduction caused by energy consumption, the improvement of air quality during the national lockdown was expected and supported by different sources, including worldwide datasets like World Air Quality Index and regional datasets like the Central Pollution Control Board-CAAQMS stations in India (Karuppasamy et al., 2020). According to Filonchyk et al. (2020), the enhancement of air quality was sligher in several less heavily-polluted cities such as Madrid, New York, Paris, Seoul, Sydney, and Tokyo. Meanwhile, air quality had a larger improvement in highly developed industrial regions such as the North China Plain and

Fig. 6. COVID-19 and the fluctuations of energy market.

Fig. 7. COVID-19 and the development of renewable energy sector.
the Yangtze River Delta, which are primary areas emitting SO2 and NO2 (Balsalobre-Lorente et al., 2020). Such variations can be explained by the degree of urbanization, population density, the number of mobile sources (for example, vehicles), and industry characteristic (Filonchyk et al., 2020). In summary, pollution-driven economies tend to witness a more significant emission reduction due to COVID-19 restrictions.

The emissions of various air pollutants act as an important role in improving air quality, which attracts research interest. The NOx generated in the process of fossil fuels combustion has experienced an abrupt decline during the pandemic (Chakraborty et al., 2020; Liu et al., 2020a; Sicard et al., 2020). Similarly, a 20% reduction in CO emissions after the Lunar New Year in east China was due to the decline of coal and crude oil usage (Filonchyk et al., 2020). Furthermore, in urban areas of São Paulo, Brazil, during lockdown (March 24-April 20, 2020), the decrease in the concentration of CO was even more obvious (up to 64.8%) compared to the same period in 2015-2019 (Yuri et al., 2020). During the same period, the emissions of PM2.5 and PM10 dropped 29.8% and 22.8%, respectively in São Paulo, Brazil, compared to previous levels of 2015-2019. The decline in the discharge amount of PM2.5 and PM10 can be obviously explained by the absence of transport activities in cities (Bao and Zhang, 2020). The shutdown of power plants and coal mining during the pandemic led to less burning of sulfur-containing fossil fuels, which are the main anthropogenic source of SO2 (Filonchyk, 2020). Therefore, the SO2 concentrations during lockdown was observed a decrease of up to 18.1% in the urban areas of São Paulo, Brazil, compared to the same period of 2015-2019 as expected (Yuri et al., 2020). However, although the emissions of SO2 decreased from 6.3 to 5.3 μg m⁻³ in urban areas of Hangzhou, China, similar to other places, it unexpectedly increased from 4.7 to 5.8 μg m⁻³ in the rural areas (Wang et al., 2020b). Such conflicted phenomena can be explained by the household heating in the winter. Specifically, low-income groups living in rural areas usually prefer using cheap sulfur-containing fossil fuels such as coal rather than cleaner energy like natural gas and electricity, leading to the unexpected increase of SO2 in rural areas (Filonchyk et al., 2020). Apart from SO2 emissions, an increase in O3 emissions was observed in Hangzhou, China. O3 concentrations increased from 24.6 to 60.6 μg m⁻³ in urban areas, and from 42.0 to 62.9 μg m⁻³ in rural areas during the lockdown, which can be explained by the weakening of chemical titration of O3 by fresh NO emissions. As shown in Fig. 9, as the limitation of economic production and transportation during the pandemic, the emissions of some pollutants such as NO2, CO, PM2.5, PM10, and SO2 plunged due to the reduction in energy consumption. Conversely, the discharge amount of O3 and SO2 (in some rural areas) unexpectedly increased.

Besides air pollutants, the lockdown policy carried out during the pandemic also played a decisive role in the subtraction of carbon dioxide emissions, which was another contributor to the air quality improvement. The carbon footprint in Italy during the lockdown period decreased by 20% compared with 2015-2019 levels due to the substantial reduction in the consumption of natural gas, oil, petroleum products, and electricity (Rugani and Caro, 2020).

Furthermore, the reduction in GHG and air pollutants emissions exerted an effect on climate. Positively, the reduction in emissions of GHGs such as CO2 and NOx may exert a short-term cooling effect on the global climate. The reduction of emissions of short-lived pollutants such as SO2 and NO2 could weaken the aerosol cooling effect, indicating an aerosol-induced warming trend (Forster et al., 2020). Under the combination of both the cooling and warming effects, Forster et al. (2020) estimated a negligible cooling of around 0.01 ± 0.005°C by 2030 compared to a baseline scenario that follows the current climate policy. According to Norouzi et al. (2020), it is still hard to assess the effect of COVID-19 on the climate change and the environment. Considering there’s no substantive or structural changes in the economic, transport, or energy systems in the short term, the decreases in the carbon emissions may be temporary, and the emissions are likely to rapidly recover or even exceed the pre-event levels.

3.1.5. COVID-19 and the energy policy

COVID-19 urges governments to formulate more public policies to mitigate the social burden and shore up economic recovery. Thereinto, in response to the COVID-19 crisis, energy policy received great attention from policymakers and researchers for its broad influences on the society, economy, and environment (Cojoianu et al., 2020). According to the goals of energy policy, it can be divided into the energy security policy and sustainable development policy (seen in Fig. 10). In addition to policy goals, policy tools and policy effects have also been summarized in this section.
As a result of isolation and lockdown policy, residential energy consumption and energy bills will rise. Moreover, many non-core positions that can’t be fulfilled remotely have been eliminated during the pandemic, leading to a surge in the unemployment rate followed by an increase in the poverty rate (Khalid et al., 2020). The higher energy expenditure and declining income caused more economic burdens in low-income households, which are more sensitive to extreme incidents like COVID-19. They are more likely to meet the problems of energy insecurity which means they may not be able to afford their energy bills in the future (Krzysztofik et al., 2020). Even worse, energy poverty will encourage unsafe heating behaviors such as burning trash, using ovens, and turning on space heaters, which may cause severe air pollution and threaten the health of residents (Chakraborty et al., 2020). As a basic human right, the provision of electricity during the COVID-19 pandemic is necessary for all populations due to the necessary needs of temperature control, adequate lighting, refrigeration, cooking, and access to the Internet (Anser et al., 2020). In this context, the establishment of an energy policy aimed at addressing energy poverty and energy insecurity is of great importance. Some countries like the US have introduced a relief policy to mitigate this problem. The US provided US$900 million in funding to the Low-Income Home Energy Assistance Program (Graff and Carley, 2020). In addition to the residential sector, the pandemic also threatened the energy security of the countries which are overly reliant on single export-orientated industries, such as crude oil and natural gas. Yaya et al. (2020) confirmed the adverse impacts on the enterprise survival in the energy industry in Africa due to the confined global energy trade during the pandemic. The sharp revenue loss of energy industry led to the vulnerability of economy. Therefore, an assistance policy is needed to support the energy industry in such countries or areas. However, in view of the mounting financial burden faced by all countries, some developing countries are unable to afford a large-scale relief policy, thus requiring an assistance policy from the international community. International funders committed assistance to Africa for this purpose, but generally in the form of loans rather than grants, which would add debt burdens to the country in the future (Yaya et al., 2020).

In addition, considering the persistently low oil prices and gradual recovery of economic activities, carbon emissions could rise even further after the COVID-19 crisis, which will deteriorate the environment and exacerbate global warming. To avoid the rebound of carbon emissions and restrict the aggravation of global warming after the pandemic, governments have put forward some green-recovery policies, like carbon pricing, carbon tax policy, development of smart grids, and removal of fossil fuel subsidies (Mukanjari and Sterner, 2020; Cojoianu et al., 2020). According to Barbier and Burgess (2020), some energy policies can help the low and middle-income countries to achieve greater progress in the Sustainable Development Goals without adding extra funding burdens. Specifically, a subsidy swap from fossil fuel to clean energy can facilitate adopting renewable energy and developing energy efficiency technologies, and the carbon tax policy can offer more fund in climate solutions through a levy on fossil fuels (Barbier and Burgess, 2020). In conclusion, researchers have emphasized the importance of formulating green-recovery policies aiming at restricting energy consumption, mitigating global warming, and promoting sustainable development.

3.2. Future research

Based on the review of each hotspot involved in COVID-19 and energy, there are some research gaps of existing researches. Therefore, the prospect for future research is proposed in this section, as shown in Table 3.

3.2.1. Energy consumption

Based on above review, the reduction in energy consumption, especially electricity consumption, among different sectors has been noticed by many researchers. Nevertheless, current researches mostly explained the general decrease in energy consumption within an industry or a nation from a macro perspective. Therefore, the impact of COVID-19 on micro households and enterprises should be highlighted based on heterogeneity characteristics like family structure, industry type, company scale, and company ownership (Gu et al., 2020).
Although many studies have investigated the relationship between COVID-19 and energy consumption, the specific influence mechanism has yet to be explored. Agdas and Barooah (2020) pointed out that the pandemic effect on electricity demand is not a simple reduction in comparable time frames, and there are noticeable differences among regions varying with weather, joblessness rate, and regional income. Hence, spatial heterogeneity should also be incorporated into related studies to explore the influence mechanism. Furthermore, future researchers should perform energy demand forecasting under the scenarios of optimism, neutrality, and pessimism according to the expected developing trend of the pandemic.

In addition, energy efficiency may be affected by pandemic (Yuan et al., 2020). For example, as an important prevention measure in an enclosed indoor environment, ventilation can reduce the infection transmission probability and bring higher energy consumption and lower energy efficiency. Thus, the ventilation control strategy should consider both infection prevention and energy efficiency (Wang et al., 2021). Triggered by the COVID-19, the acceleration of the digitalization led to the energy consumption shift from centralized public places (office and school) to distributed private households (Jiang et al., 2021). However, the net consumption change highly depends on user behaviors and energy efficiency, which are full of uncertainties and ambiguities, especially the energy efficiency of buildings deserves more researches to explore the net influence of the pandemic on total energy consumption.

3.2.2. Fluctuation of energy market

The fluctuation of the energy market is closely related to the outbreak of COVID-19, which has inevitably spread pessimism sentiment among investors and undermined the revenue forecast in the energy sector (Tahir and Batool, 2020; Khalid et al., 2020). Current researchers have investigated the negative impacts of COVID-19 on the energy market. However, according to Lee et al. (2002), the increase in risk premium could be associated with the hold-more effect in the stock market. From this point of view, the COVID-19 pandemic could have a positive effect on stock returns of crude oil industry by a higher risk premium for the extra risk caused by the pandemic.

With the rapid development of global financial markets, the relationships among financial products are increasingly complex. Due to the financial attribute of energy product, many studies have discussed the impacts of COVID-19 on the volatility of the energy price (Liu et al., 2020b; Sharif et al., 2020). However, the COVID-19 can also influence the cross-correlations between crude oil and other financial products like agricultural futures (Wang et al., 2020a). In the future, more studies are needed to explore the nexus between energy goods and other financial products or commodities.

In the background of persistent anti-epidemic status in the world, regions like Africa where the energy export is the main source of economic growth and fiscal revenues, will be more sensitive to the fluctuation in the energy market (Yaya et al., 2020). Hence, future studies should focus more on the pandemic impacts on such economies, like evaluating the economic loss from the energy market fluctuation and offering policy implications to avoid structural damage to the economy.

3.2.3. Renewable energy industry

The current pandemic shock has revealed the vulnerabilities of fossil fuels and the advantages of developing renewable energy. As Dincer (2020) stated that, regarded as a turning point from fossil energy to hydrogen energy, the outbreak of the COVID-19 pan-
demics can help achieve higher energy efficiency and better climate through the hydrogen energy options. However, few studies have evaluated the enhanced energy efficiency due to the promotion of renewable energy share, which will be an important research direction in the future. Besides, the research scope should be expanded to more types of renewables like biofuel rather than focusing on common renewables like solar and wind energy.

Besides, the technology features of renewable energy require further investigation. Most renewables support the utilization of the remote-control technology, making it more convenient to operate energy equipment during lockdown, such as sunlight-tracking sensors used in solar energy (Hosseini, 2020). However, the remote-control technology isn’t exclusive to renewable energy. Meanwhile, the traditional energy also presents the advantage of stable energy generation, while the energy production through renewables will be confined to uncontrollable environment factors such as the volume of wind and water. Therefore, the comparison in technology features, efficiency and stability between traditional and renewable energy should be conducted in the future.

Besides, in the background of COVID-19, some special technologies of renewable energy production can be further studied. For instance, by using the method of pyrolysis, the personal protection equipment widely used during the pandemic can be converted into liquid fuels (Jain et al., 2020). Such scientific disposal of substantial bio-medical waste generated during the pandemic will not just prevent severe damage to humankind and the environment but also produce a source of alternative energy and meet the growing energy needs.

In addition to the environment improvement, developing renewable energy will bring some economic benefits. In the post-pandemic era, many governments can meet the problems of economic recession and rising unemployment rate. In such a situation, developing renewable energy industry can create new employment opportunities (Hosseini, 2020). Therefore, the impacts of renewables development on the economy and society will be a hotspot as the pandemic takes a turn for the better.

Finally, despite many studies have been conducted from different angles on this hotspot, there is still no agreement on the ultimate net influence. As a result, more quantitative and macro analyses should be conducted to perform a comprehensive evaluation and explore the pandemic influences on the renewable energy industry over a longer time scale.

### 3.2.4. Climate impacts

The impact of COVID-19 on air pollution induced by energy consumption has been studied by scholars on different regional scale, but the research scope should be further expanded to more types of pollutants, such as Volatile Organic Compounds, which has a great influence on the formation of O₃ together with NOx. Moreover, current studies have mostly concluded that restrictive measures reduced emissions of major air pollutants by fewer transport activities and less fuel combustion in factories and commer-

| Table 3 | Future research. |
|---|---|
| **Hotspot: COVID-19 and changes in energy consumption** |  |
| Gu et al. (2020) | Studying the energy consumption changes in different industry | The micro analysis of firms and households |
| Aqdas and Barooah (2020) | Analyzing the general pandemic influence on energy consumption in a certain city or district | Consideration of heterogeneity analysis according to regional characteristics |
| Wang et al. (2021) | Focusing on the total level variations of energy consumption during the pandemic | Incorporation of energy efficiency into the pandemic influence on energy consumption pattern researches |
| **Hotspot: COVID-19 and the fluctuation of the energy market** |  |
| Lee et al. (2020) | Positive effects of COVID-19 | The consideration of higher risk premium caused by the pandemic |
| Wang et al. (2020a) | Studying the fluctuation of energy product and energy stocks | The study of the cor-relations between energy product and other financial products like agricultural futures |
| Yaya et al. (2020) | Studying the pandemic damage to the energy exporters | The evaluation of the economic loss from the energy market fluctuation to offer policy implications |
| **Hotspot: COVID-19 and the development of renewable energy** |  |
| Dincer (2020) | Revealing the advantages of developing renewables like higher energy efficiency and better climate | The evaluation of enhanced energy efficiency due to the expansion of renewable energy |
| Jain et al. (2020) | Introducing the pyrolysis method of turning medical waste to liquid fuels | The introduction of more special production methods of renewables |
| Hosseini (2020) | Presenting technology advantages of renewables like remote-control | The comparison in technology features, efficiency and stability between traditional and renewable energy |
| Jiang et al. (2021) | Analyzing the pandemic influence on renewable energy sector from positive and negative angles | The evaluation of net influence of pandemic on renewable energy industry |
| **Hotspot: COVID-19 and climate impacts caused by energy consumption** |  |
| Sicard et al. (2020) | Focusing on the air quality improvement due to less emission from industries | The evaluation of emission effects from the increased energy consumption in the residential sector |
| Forster et al. (2020) | Focusing on the short-term temperature change during the pandemic | The analysis of the long-term climate influence |
| Kerimray et al. (2020) | Analyzing the relationship between pollutant emissions and lockdown policy | The consideration of other influencing mechanism |
| **Hotspot: COVID-19 and energy policy** |  |
| Malliet et al. (2020) | Introducing short-term economic and environment consequences of public policies | Follow-up analysis to find out the long-term influence of the energy policies from a longer time scale |
| Sobiersalski and Hubbard (2020) | Analyzing the general policy imposed to the whole nation | Industry-level policy like jet fuel taxes on air traffic |
cial buildings. However, in terms of the residential sector, residents may increase electricity usage, thus requiring more fuel combustion in power stations. Even worse, residents in rural areas may turn to domestic heating and biomass burning during lockdown due to the longer time spent in households (Sicard et al., 2020). Considering that the residential sector could counterbalance the decrease of air pollutant emissions in the industry and transportation sectors, the pandemic impacts on air pollution induced by energy consumption should be further highlighted from both two perspectives.

Although the improvement of air quality around the world can be attributed to the lockdown measures to some extent, other influencing mechanisms also should be discussed. The lockdown measure isn’t the only reason for the reduced combustion of fossil fuels, other factors such as seasonal changes in temperature will influence coal usage in the heat and power plants or in individual households and then affect air quality. Therefore, in order to precisely evaluate the pandemic effects on air quality improvement, an analysis of COVID-19 and air pollution with the consideration of other influence factors should be conducted further. Finally, considering that climate change is a slow and continuous process, the related researches on the climate impacts of COVID-19 on a longer time scale are suggested.

3.2.5. Energy policy

According to the review results, the researches about the energy-related policies during the pandemic are commonly developed from policy target, policy tools, and policy influences. However, the literature still lacks the follow-up analyses to study the subsequent influences of these policies. Hence, the evaluation of the long-term effects of these policies in post-pandemic era will be a hotspot in the future. During the COVID-19, governments have taken many emergency measures to boost the downward economy, such as fiscal stimulus or consumption subsidy, which are usually short-term policies (Malliet et al., 2020). However, the transition from fossil fuels to a sustainable, low-carbon energy system will require long-term (5-10 years) commitments of public spending and pricing reforms. Therefore, future researchers should consider the energy policies from a longer time scale. Apart from the general policy imposed to the whole economy, some researchers tried to study the policy focused on a certain industry, like the jet fuel taxes on air traffic (Sobiersalski and Hubbard, 2020). The energy policy concentrating on a more specific domain will be a hot topic for future studies and may aid policymakers to make a more targeted policy.

3.3. Research methodologies

The methodologies used in the selected 59 articles can be divided into quantitative and qualitative analysis. Among them, a regression model, as a common quantitative method, has been conducted on 15 articles, especially in the hotspots of the pandemic impacts on energy consumption and air pollution (Anser et al., 2020). The nexus between COVID-19 and energy system are commonly investigated by using machine learning, which can improve the efficiency and accuracy of the conventional regression, especially in the prediction of energy demand (Duf et al., 2020). In addition, many studies analyze the impacts of the pandemic on energy system based on the qualitative methods like causal analysis, comparative analysis, and contradiction analysis. Meanwhile, scenario analysis is most widely applied to explore the impact of COVID-19 on the energy system in different expected situations, usually followed by a comparative analysis to compare the differences between various scenarios.

3.3.1. Regression model

To explore the impacts of COVID-19 on the energy, the regression model has been widely used to examine the intensity and characteristics of such impacts based on different data source, research scales and research issues (Fezzi and Fanghella, 2020; Štifanić et al., 2020; Mukanjari and Stenner, 2020). More concretely, it has been most applied to assess the impacts of COVID-19 on energy consumption (Gu et al., 2020; Agdas and Barooah, 2020; Fezzi and Fanghella, 2020) and air pollution (Bao and Zhang, 2020; Anser et al., 2020). In addition, regression analysis has been applied to predict the energy demand or price (Lee et al., 2002; Linghu et al., 2020; Norouzi et al., 2020), and assess the pandemic shock to stock performance of enterprises in different industries (Mukanjari and Stenner, 2020). As shown in Table A1 in appendix, the specific settings of dependent, independent and control variables have been presented in detail.

First, the impacts of COVID-19 on energy consumption were assessed based on various regression models, like fixed effects (FE) regression model and difference-in-difference (DID) model (Agdas and Barooah, 2020; Fezzi and Fanghella, 2020). In terms of regression analysis framework, electricity consumption or demand was usually selected as the dependent variable. However, the independent and control variables within different regression models may vary. Second, the OLS linear regression and panel regression have been applied in assessing the pandemic impacts on air pollution. In this research, the dependent variables were usually indicators presenting the situation of air pollution or air quality, such as Air Quality Index, air pollutant (SO2, PM2.5, PM10, NO2, and CO) emissions, and carbon emissions. The independent variables tend to be the indicators that can describe the severity of the pandemic, like infection rate and death cases. Third, regression analysis has been adopted by some researchers for other purposes. For example, the auto-regression model was commonly applied in predictions of both energy demand and energy price (Štifanić et al., 2020). To extract other influencing factors of energy demand, factors such as Gross Domestic Product, purchasing managers’ index, foreign direct investment, exports, and demand of other energy can be controlled in regression function (Norouzi et al., 2020).

The regression model is a common and effective tool to analyze the impacts of COVID-19 on the energy system in its most simple and well-understood form. Apart from the traditional regression models, some researchers have made some improvements in their researches. For instance, considering the nonlinear and chaotic characteristics of oil prices, Bildirci et al. (2020) applied the Logistic Smooth Transition Autoregressive Generalized Autoregressive Conditional Heteroskedasticity (LSTARGARCH) model, which allows STAR-type nonlinearity in both the conditional mean and variance (Lee et al., 2002). In addition, Linghu et al. (2020) have used the Seasonal Auto Regressive Integrated Moving Average (SARIMA) model based on time series data to predict the monthly demand for Coalbed Methane.

3.3.2. Neural networks model

COVID-19 has caused uncertainties and fluctuations in the energy market (Tahir and Batool, 2020). Predicting energy demand and price accurately is critical for governments and investors. Regarding prediction models, artificial intelligence algorithms such as machine learning methods, especially artificial neural networks (ANNs) have been widely used, which contribute to enhancing the accuracy and efficiency of forecasting (Norouzi et al., 2020; Ou et al., 2020; Štifanić et al., 2020; Sewdien et al., 2020).

According to Table A2 in appendix, energy demand is usually selected as an output variable within the ANNs model. In terms of input variables, infections, and a series of macroeconomy indexes including Foreign Direct Investment, exports, and purchasing manager index are used. In addition, Štifanić et al. (2020) adopted the
bidirectional recurrent neural network (BRNN), which is a class of the ANNs model. Regarding the BRNN model, a signal can travel both forward and backward by introducing additional hidden layers in which data were placed in the opposite, negative direction (Štífanić et al., 2020).

ANNs has demonstrated some advantages in demand or price prediction in the background of the COVID-19 pandemic. First, ANNs does not necessarily require comprehensive knowledge about the relationship between input and output variables (Norouzi et al., 2020). During the pandemic, the volatility of energy price and energy demand presents a nonlinear and chaotic structure. However, the application of ANNs can reveal the complex relations between input variables and output variables by rectifying linear units as the activation node, which can be in any form of function. Second, with more added nodes, an increasingly complex ANN model can be applied to process the multivariable data of any large scale. Lastly, the utilization of ANNs can minimize the experimental time and operating cost compared with other methods (Suganthi and Samuel, 2012).

To provide a reliable forecasting, new techniques should be adopted in future studies. For example, Artificial Intelligence algorithms such as dynamic programming, genetic programming, and combination of convolutional neural networks and long- short term memory method can be adopted to test robustness.

### 3.3.3. Computable general equilibrium model

Global governments have implemented many policies to mitigate the adverse consequences of COVID-19. To assess the policy effects in the short and long term under COVID-19, the computable general equilibrium (CGE) model has been widely used (Aydin and Ari, 2020; Lahcen et al., 2020; Malliet et al., 2020). Within the framework of the CGE model, all of the relationships among economic variables are described, which is suitable to evaluate the impacts of external shocks (Lahcen et al., 2020). To explicitly explain the applications of CGE model, we have summarized the external shocks and the variations within the model, respectively in Table A3 in appendix.

To investigate whether implementing carbon pricing can yield positive macroeconomic dividends in the post-pandemic era, Malliet et al. (2020) used ThreeME which is a country-level open-source CGE model to evaluate the short-, medium-, and long-term impacts of environmental or energy policies at the macroeconomic and sectoral levels (Malliet et al., 2020). The feature of ThreeME relies on the dynamic feedbacks between supply and demand, where prices and quantities adjust slowly, allowing for situations of market disequilibria. In addition, Lahcen et al. (2020) used a static CGE model to simulate the impacts of green investment policy on the macroeconomy and climate. In view of the industry heterogeneity, a multisectoral computable general equilibrium model, ORANI-G, is employed (Aydin and Ari, 2020).

There are some advantages of using the CGE model compared to traditional econometric methods. On the one hand, the econometric methods always focus on a single market or a single sector, while the CGE model can comprise all sectors and markets, enabling it to simulate the interactions among all economic subjects, including residents, enterprises, and governments in an entire economic system. Therefore, it can be used to assess the influences of COVID-19 from a macro and comprehensive perspective. On the other hand, the conventional econometric models are not based on the optimal behavior of consumers or producers. However, the CGE model can address this problem by setting a set of equilibrium equations grounded in the economic theory of optimal behaviors, thus facilitating insights in its underlying mechanism. Furthermore, considering the dynamic impacts of COVID-19, researchers need to provide a quantitative assessment of these exceptional measures both in the short and long term. In particular, the imbalances of the market caused by pandemic cannot be modelled in the static model. Hence, dynamic models like Dynamic Stochastic General Equilibrium can be used in the research on this topic (McKibben and Fernando, 2020).

Though CGE models have the advantage of identifying multiple sectors in the economy, they have the disadvantage of annual periodicity and so are unable to capture accurately the short, sharp nature of pandemic shock. Therefore, the CGE models will demonstrate better performance with the combination of macroeconomic models featuring the quarterly periodicity and single-sector models, which are exactly complementary to CGE models (Verikios, 2020).

### 3.3.4. Scenario analysis

Scenario analysis, as a common qualitative method, has been widely used in different domains (Yuan et al., 2020). As shown in Table A4 in appendix, researchers commonly set baseline scenarios (business as usual) and compared scenarios according to economic indicators and pandemic development. For example, to analyze the impacts of the falling oil price on the macroeconomy in Turkey, Aydin and Ari (2020) set a baseline scenario in which the pandemic situation and oil price stay the same, while the other two compared scenarios are presenting a 25% and 50% reduction in oil price, respectively. Besides, Rugani and Caro (2020) set scenarios according to the GDP index. The 1.3% increase of GDP compared to 2019 was selected as a baseline scenario to compare with other scenarios with a decrease of 4.7% and 9.1%, respectively.

In addition, some researchers may set scenarios qualitatively according to the pandemic development. For example, Malliet et al. (2020) regarded the situation without COVID-19 and climate policy as the baseline scenario, while the situation involved them as comparing scenarios. Similarly, in the study by Meles et al. (2020), the situation before the pandemic was set as a baseline scenario, and the comparing scenarios have been set from two perspectives, including maintaining the current climate policy and modifying the climate policies. Furthermore, some researchers may conduct the scenario analysis among neutral, pessimistic, and optimistic situations according to the expectations of the severity of the pandemic.

Considering the uncertainties and turbulence within energy system brought by COVID-19, it is necessary to discuss the future development of the energy system under various scenarios. Furthermore, scenario analysis can be integrated with other models such as the ANNs and CGE model, which can provide a more comprehensive understanding of the relations between COVID-19 and the energy.

### 4. Conclusions

Considering the ongoing pandemic and the turbulent international environment, the impacts of COVID-19 on energy will be profound and dynamic. Therefore, we conducted a systematic review to offer a comprehensive assessment of the existing researches on this topic through bibliometric analysis. The main findings are concluded as follows.

First, the impacts of COVID-19 on energy are mainly reflected in five aspects: energy consumption, energy market, renewable energy, climate impacts, and energy policy. Thereinto, many pandemic effects on energy are transmitted through the response policies of the government. Specifically, the reduced energy consumption in the industry and transport sector and increased consumption in the residential sector are resulted from the lockdown policy. The renewable energy supply chain has been disrupted by the border closure policy. Less fossil fuel combustion led to the improvement of air quality due to the shutdown policy of heavy industries. Meanwhile, some effects are directly sourced from the COVID-19 pandemic.
pandemic to some extent. For example, the pandemic may lead to energy market fluctuation through the imbalance of demand and supply. The pandemic may encourage energy policies to overcome the ascending unemployment and poverty rate. Moreover, the pandemic exerted both negative and positive impacts on energy. On the one hand, both the demand side and supply side of energy have been influenced, resulting in a series of negative shocks, like slashing energy demand, inhibiting the stable energy supply, increasing the energy market volatility, and threatening the energy security. On the other hand, the current pandemic also brought some dividends and opportunities, like enhancing air quality and encouraging the transition to a more renewable and sustainable energy system. According to the pandemic impacts on energy, we found some weakness and insufficiency of the current energy system, including unstable price mechanism of fossil fuels, high dependence on labor force, and rigid production mode.

Second, the researches on the COVID-19 and energy are still in the infancy, bringing much difficulties in covering all the facets of pandemic effects on energy by the current study. Therefore, we put forward several important research directions to offer references for future researchers. Specifically, the long-term influence of the COVID-19 on energy should be explored further based on the short-term research results; the studies about the transition towards renewable and sustainable energy system should be strengthened in the post-pandemic era; the pandemic effects on energy efficiency should be fulfilled.

Third, the review of research methodologies used in related studies indicated that the regression model has the most extensive application, especially regarding the impacts of COVID-19 on energy consumption and air pollution. For the micro research, to enhance the prediction efficiency of energy demand or price, artificial neural network was usually applied in combination with traditional regression methods. For the macro research, the CGE model is a popular method used to assess the effects of energy-related policies or to study the impacts of COVID-19 on the macroeconomy of a nation. In addition, scenario analysis has been adopted by many studies to analyze the pandemic influences of different scenarios in the future.

However, this research is limited to the data source which is confined in articles collected from the Web of science within a certain period. The information about COVID-19 and energy obtained from other data sources such as working papers and reports may be neglected. Besides, in light of the ongoing pandemic and persistent work on this topic, some long-term and profound impacts of pandemic may have not been detected and fully studied.

Based on the above findings, some implications are obtained from both theoretical and practical perspectives. From the theoretical perspective, through the bibliometric analysis applied to explore the hotspots involved in COVID-19 and energy, the influence mechanism and research methodologies are reviewed to provide the theoretical foundation and practical tools. Then, future research is put forward to extend research areas and offer more research ideas. Besides, the practical implications can be drawn as follows. First, to address energy insecurity and energy poverty exacerbated by COVID-19, it is suggested that governments should implement more relief policy or consumption subsidy. Second, considering the uncertainties of global supply chains and international trading, it is essential to gain independence of raw materials and core technology to protect and develop the renewable energy industry within a nation, especially in some less-developed countries. Therefore, governments are suggested to attach more attention to core energy technology to resist external risks. Third, major oil exporters can take the chance of low oil price to increase the strategic reserve of crude oil to safeguard national energy security. Besides, energy producers can organize and resume under the premise of labor safety to guarantee global energy supply. Finally, with the mend of the pandemic and the relaxation of the lockdown policy, governments may conduct a series of fiscal stimulus and lax monetary policies to recover from the recession, which may bring a surge in carbon emissions and offset the former reduction emission effects. Therefore, affordable green-recovery policies are encouraged to sustain the relationship between economic growth and sustainable development. Moreover, the upgrade and optimization of energy structure are suggested to avoid severe air contamination caused by fossil fuels.

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.

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Appendix

Table A1–A4
Table A1
Regression model used in COVID-19 and energy.

| Ref.                     | Method                                      | Dependent variable                          | Independent variable                                      | Control variable(s)                                                                 |
|-------------------------|---------------------------------------------|----------------------------------------------|------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Hotspot: The impacts of COVID-19 on electricity consumption/demand | Linear regression (weather correction)     | Electricity demand                           | Days passed from the January Weather                       | Daily peak hourly demand; Demand ramp rate; Net interchange of electricity            |
| Agdas and Barooah (2020)| Fixed-Effect model                          | Electricity load                             | Interaction item (week-of-the-year fixed effects and a dummy variable identifying 2020) | Week-of-the-year fixed effects; Dummy variables identifying the day; Dummy variables identifying holidays |
| Gu et al. (2020)        | Difference-in-Difference model              | Electricity consumption (in aggregate level) | Interaction item (whether lockdown and whether return to work) | Firm fixed effect (absorbs firm heterogeneity); Date fixed effect (eliminates the time-specific impact) |
| Hotspot: The impacts of COVID-19 on air pollution | Univariate linear regression                | NO₂ emission                                 | Traffic density                                            | NA                                                                                   |
| Wang et al. (2020b)     | Linear regression                           | O₃ emission                                  | NO₂ emission                                               | Knowledge spillover; Electric power consumption; Economic crisis; Population density  |
| Anser et al. (2020)     | Linear regression                           | NO₂ emission                                 | PM₂.₅ emission                                             | Weather (daily mean temperature)                                                    |
| Bao and Zhang (2020)    | Dynamic panel model; Least Square Dummy Variable model | Air Quality Index; Main air pollutants emissions | Air Quality Index (last period); Whether lockdown          |                                                                                      |
| Regression analysis used in other hotspots | Multivariate linear regression model | Demand of electricity/oil | Severe of COVID-19; Infected population | Gross Domestic Product; Purchasing managers' index; Foreign direct investment; Exports; Demand of other energy |
| Norouzi et al. (2020)   | Fixed-Effect model; Cross-sectional regressions | Abnormal return of firms | Carbon intensity                                            | Industry fixed effects; Country fixed effects; Firm characteristics (firm size, profitability and leverage) |
| Albulescu (2020)        | Autoregressive Distributed Lag model        | Economic policy uncertainty                  | Severe of COVID-19; Crude oil price                        | Economic policy uncertainty in last period                                           |

Table A2
Neural networks model used in COVID-19 and energy.

| Ref.                     | Methodology                                      | Input variables                              | Output variables                                    |
|-------------------------|-------------------------------------------------|----------------------------------------------|----------------------------------------------------|
| Štifanić et al. (2020)  | Bidirectional recurrent neural network           | Crude Oil price; Stock market indexes; Confirmed cases Infections; Foreign Direct Investment; Exports; Manufacturing Purchasing manager index; Industrial Production; Stocks; GDP growth | Future movement of Crude Oil price; Crude Oil price; Petroleum demand |
| Norouzi et al. (2020)   | Neural network- based sensitivity analysis      | Pandemic data; Government policies; Demographic data Mobility data; National household travel data; Historical weekly fuel demand Atmospheric quantities (wind speed, direction, temperature and pressure); Physical properties (terrain ruggedness index and wind farm layout); Numerical weather predictions | Variations in mobility; Future motor gasoline demand |
| Ou et al. (2020)        | Neural networks                                 | Daily temperature (maximum, minimum, and average); Density of a city; Relative humidity; Wind speed | Wind power generation |
| Sewdien et al. (2020)   | Neural networks                                 |                                              | Number of confirmed cases for 30 days               |
| Pirouz et al. (2020)    | Group method of data handling type of Neural networks |                                              |                                                    |
Table A3
Computable general equilibrium model used in COVID-19 and energy.

| Ref.          | Model          | External variables                        | Changes within the model                        |
|--------------|----------------|-------------------------------------------|--------------------------------------------------|
| Malliet et al. (2020) | ThreeME       | Carbon pricing policy                     | Increase fossil energy price;                    |
|              |                |                                           | Substitution of energy to capital;               |
|              |                |                                           | Enhance the efficiency of energy investment     |
| Lahcen et al. (2020) | Static CGE model | Green investment policy                  | Encourage economic growth;                       |
|              |                |                                           | Reduce emissions                                 |
| Aydin and Ari (2020) | ORANI-G        | Falling oil price                         | Compensate the losses in other sectors by low    |
|              |                |                                           | energy price                                    |
| Verikios (2020) | Global CGE model | Preventative measures                    | Reduce the global GDP at 3% and 27% in the first  |
|              |                |                                           | two quarters of 2020;                           |
|              |                |                                           | Reduce labor productivity                      |
| Keogh-Brown et al. (2020) | CGE model | Direct disease effects; Preventive public actions | The indirect costs of mitigation or suppression of pandemic may impose unprecedented economic impacts on the UK economy |

Table A4
Scenario analysis used in COVID-19 and energy.

| Ref.          | Baseline scenario                                                                 | Comparing scenarios                                                                 |
|--------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Aydin and Ari (2020) | Scenario-1: Oil prices and COVID-19 situation stay constant. | Scenario-2A: The rate of falling oil prices is 25%. Scenario-2B: The rate of falling oil prices is 50%. |
| Rugani and Caro (2020) | Business as Usual: 1.3% increase in the GDP compared to 2019 | Optimistic Scenario: 4.7% decrease in the GDP for the first quarter of 2020 compared to 2019 |
| Malliet et al. (2020) | Without COVID-19 or Climate Policy | Pessimistic Scenario: 9.1% decrease in the GDP for the first quarter of 2020 compared to the 2019 |
| Meles et al. (2020) | Business as usual: Before the pandemic | Scenario-1: Climate Policy |
| Ou et al. (2020) | Under the current lockdown situation | Scenario-1: COVID-19 |
| Lahcen et al. (2020) | Business-as-usual scenario | Scenario-2: Decrease in working time by 10% |
| Safarian et al. (2020) | NA | Scenario-3: A 90% overall demand, only essential sectors remain 100% active |
|                 |                             | Scenario-4: A 90% overall demand |

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