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Review:

Impacts of the COVID-19 pandemic on the energy sector*

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Abstract: The outbreak of coronavirus disease 2019 (COVID-19) has had a considerable impact on every industrial sector. As a pillar of economic development, the energy sector is experiencing difficult times during the global pandemic. This paper reviews the impact of the pandemic on the global energy sector in terms of demand, price, employment, government policy, counter-measures, and academic research, and focuses on the two largest energy countries in the world: China and the United States. Although the virus has dramatically impacted the energy sector, action to address climate issues has not been suspended, but has become more urgent than ever. Experts have pointed out that it is time to promote the transition to clean energy vigorously. Thus, here we discuss progress towards clean energy transition, including bioenergy, mineral resources for clean energy techniques, batteries, and electrolyzers. The results indicate that supply chain stability, energy storage, and policymaking during the epidemic period and post-epidemic period are significant challenges for the transition to clean energy. However, the transition can also bring new opportunities for employment, economic recovery, and the human living environment.

Key words: Coronavirus disease 2019 (COVID-19); Energy sector; Energy policy; Clean energy transition; Bioenergy; Battery; Electrolyzer
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1 Introduction

At the beginning of 2020, the 2019 coronavirus disease (COVID-19) broke out on a global scale. It killed many people and had a significant impact on the global economy. According to the COVID-19 statistical system developed by Johns Hopkins University (JHU), as of June 28, 2021, there were 181 102 393 infections worldwide and 3 923 132 deaths. The United States, India, and Brazil are the three countries with the highest number of infections and deaths in the world. Many countries have issued restrictions to slow down the spread of the virus, such as the closure of educational institutions, partial or full lockdowns, and working from home. In this context, transportation, catering, entertainment, medical care, manufacturing, real estate, and other aspects have been adversely affected. As a result, more than half of the global population has been greatly affected by containment measures (IEA, 2020). It is not hard to imagine that, as a pillar of the global economy, the energy sector has suffered a lot.

Many scholars have discussed and analyzed the impact of COVID-19 on energy and the environment. Zhang LY et al. (2021) determined the current research hotspots of COVID-19 in the energy field through bibliometric analysis, including energy consumption,

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energy markets, renewable energy, climate, and energy policy. They pointed out that regression analysis and scenario analysis are common methods of quantitative and qualitative research. Kang et al. (2021) analyzed the changes in energy consumption of different types of buildings in South Korea under the influence of COVID-19. Wang et al. (2021) analyzed the impact of the epidemic on energy consumption in China. Zhang XX et al. (2021) investigated the impact of the epidemic on the energy consumption and carbon emissions of China's transportation industry and concluded that the impact was far greater than that of Severe Acute Respiratory Syndrome (SARS). Hoang et al. (2021) studied the impact of the epidemic on the global energy system and analyzed the opportunities and challenges of transitioning to renewable energy. Yousaf (2021) explored the transmission of risk from the epidemic to the metals and energy markets. The results showed that the risk of the epidemic will not be transmitted to the industrial metals market, but it will have a great impact on the volatility of the West Texas Intermediate (WTI) oil market. Al-Saidi and Hussein (2021) evaluated the significance of the epidemic in the water-energy-food nexus. Research revealed that medicalization and demand fluctuations are key influences, and that the World Economic Forum lacks risk-based analysis. Szczygielski et al. (2021) studied the impact of epidemic-related uncertainty on energy stocks and proposed a new method for measuring the overall impact of uncertainty. Cortiços and Duarte (2021) explored the impact of the epidemic on the energy efficiency of high-rise office buildings in the United States. Jiang et al. (2021) studied the impact of the epidemic on energy demand and consumption, and highlighted future challenges, lessons, and opportunities. In addition, many scholars have analyzed the impact of the epidemic in other fields (Amir and Khan, 2021; Deshwal et al., 2021; Haqiqi and Horeh, 2021; Narasimha et al., 2021). However, previous studies did not discuss other key subsidiary issues of the energy industry, such as batteries and mineral resources used in clean energy.

Thus, the motivations for this study were:

1. To estimate the impact of COVID-19 on the energy sector;

2. To describe COVID-19 countermeasures and policies made by China and the United States;

3. To provide research managers with some references by discussing future opportunities and challenges.

The primary contributions of this paper are:

1. Changes in the global energy sector, especially in China and the United States, are described from different aspects;

2. Research focusing on COVID-19 in the energy field is summarized;

3. The future development focus, opportunities, and challenges of the energy sector are summarized.

The innovation of this paper is that we discuss some problems ignored in other papers, such as the impact of COVID-19 on unemployment, bioenergy, mineral resources needed for clean energy technology, and the production of batteries and electrolyzers. The opportunities, challenges, and lessons presented can guide managers to make better decisions and promote the development of clean energy.

2 Methodology

This study was developed based on academic databases and online resources. The selection of literature was divided into three steps:

Step 1: Literature search

Academic and general searches were used to collect relevant information. ScienceDirect and Google Scholar were used as academic search tools, and Google and Bing as general search tools. Since the theme of this paper is the impact of COVID-19 on the energy sector, "COVID" and "energy" were determined to be key words.

Step 2: Literature screening

In the search results, some publications mentioned "COVID-19" and "energy", or simply mentioned the influence of COVID-19 on the energy sector. However, the main content of some studies was not consistent with the subject of our search. In addition, the source of some literature was vague, and authenticity could not be confirmed. Thus, it was necessary to screen the literature by reading abstracts and conclusions. The following principles were applied:

1. The main content of the resource is the influence of COVID-19 on the energy sector.

2. The types of resources are limited to academic papers, reports, and forums. Academic papers should

have been peer-reviewed; reports should come from well-known institutions or enterprises; forum content should come from well-known publishing houses.

3. Data have reliable sources, and non-first-hand data will not be used.

Finally, 53 resources were selected. Among them, academic papers were from ScienceDirect, Nature Press, etc.; reports were from the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), BW Research Partnership, etc.; forum content was from IEA, Solar Power World, the Canadian Press, etc.

Step 3: Required information extraction

Extract valuable information and data from selected resources through careful reading.

3 Review findings

The literature review showed that the impact of COVID-19 on the global energy sector could be described in terms of the following six aspects: energy demand, energy price, employment, energy policy, countermeasures, and academic research. To help managers make more targeted policies, this paper focuses on the two largest energy countries: China and the United States.

3.1 Renewables increased while demand for other energy sources declined

According to statistics from the IEA (2020), global energy demand in the first quarter of 2020 (2020 Q1) decreased by 3.8% (150 mtoe) compared with the same period in 2019 due to reductions of economic activity and traffic caused by lockdowns (mtoe: million tons of oil equivalent). Based on the analysis from IEA, global energy demand will have dropped by 6% in 2020. If the economy is re-started and the virus's spread is effectively contained, the energy demand drop will be controlled at 4%. However, restarting the economy is difficult because it may lead to a second large-scale outbreak of the virus and have a more negative impact on the energy sector. In 2020 Q1, the consumption of various energy sources changed to variable degrees compared to 2019 Q1. The rate of change, causes, and countries (or regions) that were most affected are shown in Table 1. The IEA forecast the rate of change in energy demand in 2020 compared to 2019. The decline in oil demand was forecast to be the largest, reaching 9%; the forecast declines in natural gas and electricity were the same, reaching 5%; the forecast growth rate of renewable energy was 1%. Such a reduction in energy consumption has not been seen in 70 years, and was more than that caused by the financial crisis in 2008.

The IEA predicted the energy demands of some major countries and regions around the world. Fig. 1a reveals that after China imposed a lockdown at the end of January 2020, it became the country with the largest drop in crude oil demand in February and March, easing in April. After the lockdown in the United States in March, crude oil demand dropped significantly. This will have led to a substantial decline from April to June, easing in July. Demand for crude oil in the rest of the world was expected to decline significantly from March to July, easing in August. Fig. 1b indicates that global electricity demand in 2018 increased, whereas in 2019 only China's electricity demand increased. In 2020, due to the impact of the pandemic, global electricity demand was forecast to decrease, and the rate of decline in electricity demand in the United States was expected to be higher than that in China. Fig. 1c implies that global natural gas demand fell slightly in 2020 Q1, and annual demand was expected to drop by about 5%. China's natural gas demand rose in 2020 Q1 and was expected to rise by about 6% throughout the year. The decline in natural gas demand in 2020 Q1 in the United States was expected to be slightly higher than the rate of decline for the whole year. Fig. 1d shows that the demand for renewables increased in 2020 Q1 and was expected to show a slight increase throughout the year, and its share of power generation was forecast to increase.

The IEA also conducted a regional study showing the relationship between the degree of lockdown and the decline in energy demand. It revealed that the degree of restriction was different in different countries or regions around the world, and the restriction conditions were not uniform. China was the first country to have a pandemic, and the severity in each province differed, so the degree of lockdown differed. The restrictions in Hubei Province (the province in which Wuhan is located) were the strictest. The United States adopted a partial lockdown after the outbreak, but there was no mandatory requirement for isolation at home. Oxford University, UK developed a government response stringency index to measure

Table 1 Energy demand changes and reasons in the first quarter of 2020 (data source: IEA (2020))

Energy type	Change compared to 2019 Q1	Reason	Remark	Impact on China	Impact on the United States
Oil	−5%	1. Decline in the vehicle (decreased by 50%) and aviation (decreased by 60%) usage; 2. Decline in car sales	Gasoline is the oil product with the most significant drop in demand	The decline of Q1 reached 13%	The reduction of Q1 reached 0.8 million barrels per day
Natural gas	−2%	1. Demand for electricity is lower than before	The consumption of natural gas in power generation decreased by 7%, with the highest proportion of the decline	Flat	The decline of Q1 reached 3%
Coal	−8%	1. Demand for electricity is lower than before; 2. The competitiveness is not as good as natural gas	China's coal consumption trend may change global coal development. The outlook for coal depends on electricity demand, and it has the highest level of uncertainty in the development of all fuels	The decline of Q1 reached 8%	The decline of Q1 reached 30%
Electricity	−2.5%	1. The reduction of industrial production and economic activity; 2. The average temperature in the first quarter of 2020 is higher than that in 2019	Electricity demand is mainly driven by residential demand. It has the greatest impact on the service sector and the smallest impact on industrial production	The decline of Q1 reached 6.5%, the highest in the world	The decline of Q1 reached 4.5%
Renewables	1.5%	1. Additional output from new wind and solar projects	Although COVID-19 has resulted in delays in construction and supply chain, renewable energy generation has increased by 5%. The growth rate of renewable power generation capacity is likely to decline in 2020	The proportion of electricity generated by renewable energy has increased	The proportion of electricity generated by renewable energy has increased

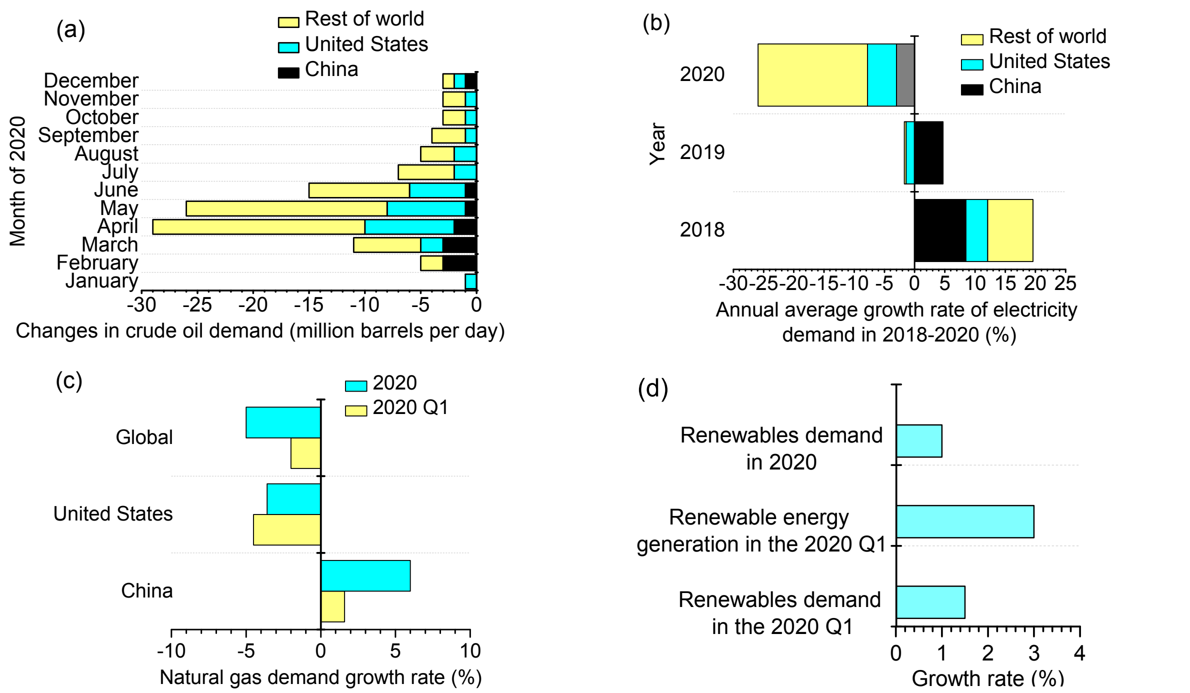

Fig. 1 Changes in energy demand in some countries or regions (data source: IEA (2020)): (a) oil; (b) electricity; (c) natural gas; (d) renewables

governments' responses to COVID-19 (Fig. 2). This index considers nine factors, including school closures and travel bans (Petherick et al., 2021). It can be inferred from the IEA's report that the stricter the lockdown, the more the weekly energy demand declined. Although China, with a high level of lockdown, had a high rate of decline in its weekly energy demand (15%), the annual energy demand decline may be lower due to timely control of the pandemic. According to IEA's forecast, China's energy demand was expected to have dropped by 4% in 2020, while the United States' demand was expected to drop by 9%.

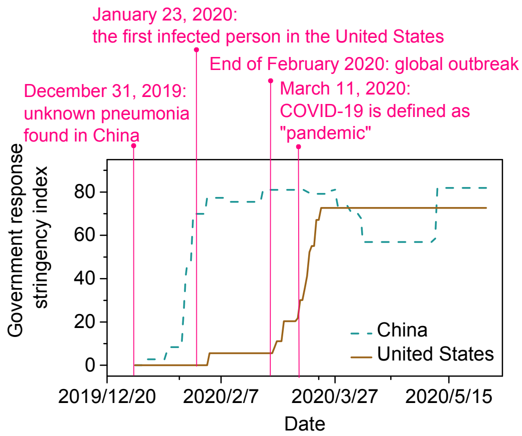

Fig. 2 Government response stringency index after the COVID-19 outbreak in China and the United States (source: University of Oxford (2020))

3.2 Oil prices declined most

Energy prices change due to changes in energy supply and demand. Since the outbreak of the pandemic, crude oil prices have continued to decline, and for the first time in history, there was a negative value, with the lowest price of −40.32 USD per barrel (Fig. 3a). This is because the demand for crude oil was so low that the oil storage facilities were almost full, and the market crashed. Due to the correlation between coal prices and crude oil prices, coal prices continued to decline, but rebounded early in April 2020. This was because China is a large coal consumer and it restarted the economies of some provinces early in April, leading to rising coal demand. Overall, the decline in coal prices was lower than that in crude oil, and short-lived. The price of natural gas was minimally affected by the pandemic and fluctuated in 2020 Q1, with a slight decrease overall. Due to

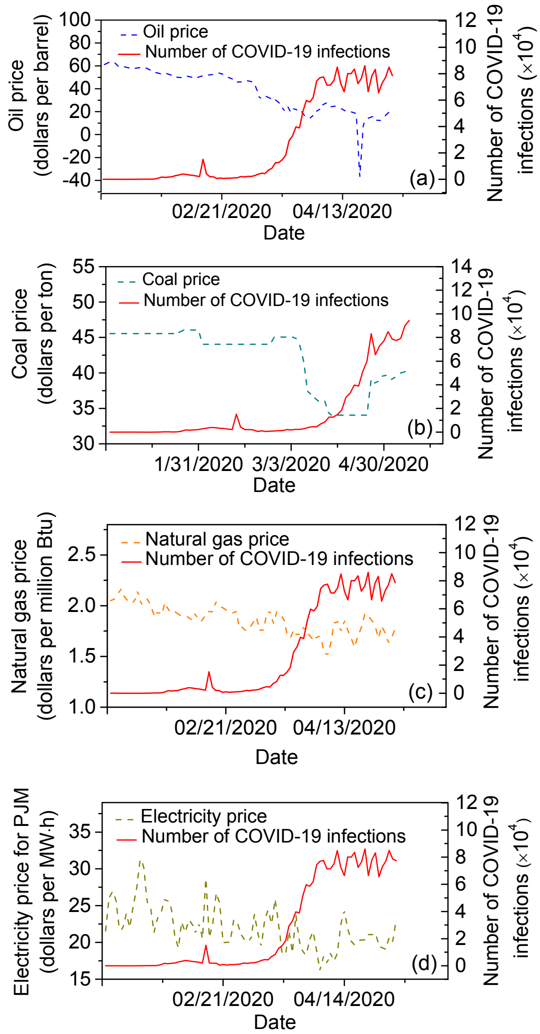

Fig. 3 Energy prices during the outbreak. (a) oil price (WTI); (b) coal price (United States); (c) natural gas price (Henry Hub); (d) electricity price (PJM)

Btu: British thermal unit; PJM: PJM Interconnection. PJM is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia

the reduction in economic activity during the pandemic, the consumption and price of electricity reduced. In 2020 Q1, electricity prices generally showed a downward trend because of the increased intensity of the lockdown. Taking the United States as an example, the average electricity price in February 2020 was lower than that in the same month in 2019. However, the average residential electricity price in February was higher than that in February 2019. This may have been because of an increase in residential electricity consumption due to home isolation.

3.3 Unemployment continued to grow

Due to restrictions, some energy companies shut down. This led directly to lower corporate profits which, coupled with lower energy prices, resulted in some energy companies implementing layoffs to save money. A report from the BW Research Partnership shows that in April 2020, the clean energy industry in the United States lost 447 200 jobs, and the employment rate fell by 17% (Jordan, 2020a), which was much higher than the 3.1% fall in March (Jordan, 2020b). Among the states, Hawaii had the highest unemployment rate (6.4%) in March 2020 (Fig. 4a) and Georgia had the highest unemployment rate (29.9%) in April 2020 (Fig. 4b). These data indicate that the unemployment rate in the United States in April was much higher than in March.

Fig. 5 reveals that 65%–70% of total clean energy unemployment was in the energy efficiency sector, the highest of all sectors. However, these data

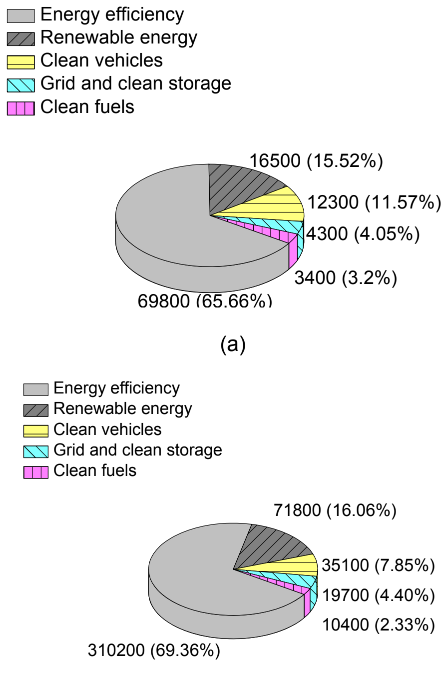

Fig. 5 Unemployment structures of the clean energy sector in the United States: (a) March 2020; (b) April 2020

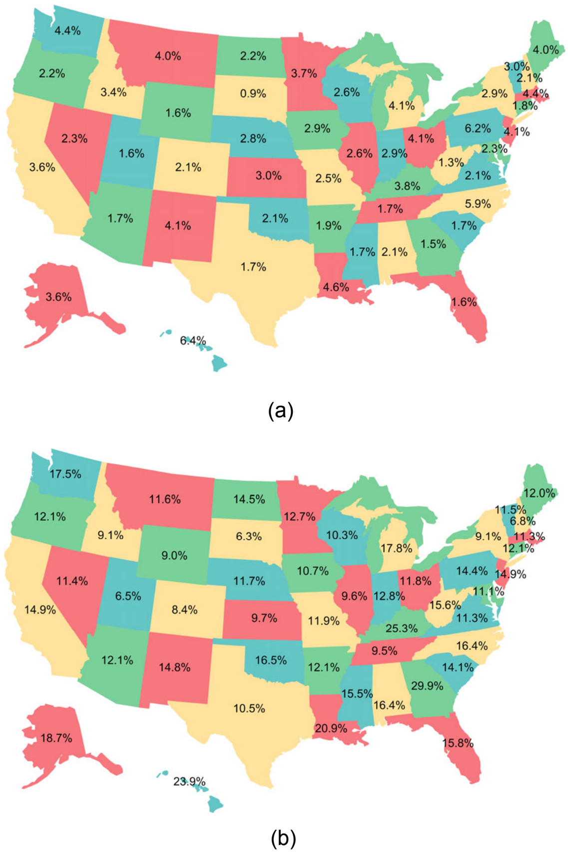

Fig. 4 Unemployment rates in the United States: (a) March 2020; (b) April 2020

are only initial estimates, and do not include underemployed workers or those on temporary leave. The BW Research Partnership also estimated that in the United States clean energy sector would lose 850 000 jobs by 2020 Q2 without policy countermeasures (Jordan, 2020a). Although the United States government introduced the "Coronavirus Aid, Relief, and Economic Security Act" (CARES) (U.S. Department of the Treasury, 2020), unemployment in the clean energy sector was not included in the subsidy. Therefore, experts estimated that the clean energy sector might not be able to recover in the short term. From the perspective of China, although there are no specific data showing the unemployment rate in the energy sector during the pandemic, based on macro data, the urban unemployment rate in China in February, March, and April 2020 was 6.2%, 5.9%, and 6.0%, respectively. These rates are similar to those during the SARS outbreak in 2003 and the financial crisis in 2008 (Cheng, 2020). In China, after the outbreak was contained in April 2020 and the economy partially restarted, some energy companies recruited new employees. To fulfill social responsibilities, some large state-owned energy enterprises also increased their recruitment. It is reported that

PetroChina, Sinopec, and China National Offshore Oil Corporation (CNOOC) increased their total workforce by 6500 jobs in 2020. It can be inferred from the above data that although the employment rate of China's energy industry was greatly affected by the pandemic, with active cooperation between the government and business enterprises, the impact of COVID-19 on employment will not last long.

Although employment in the energy industry was hit badly, there was one exception. The energy storage industry may not have been as severely affected by the pandemic as the clean energy industry due to the reduction of overall energy consumption and the increase in demand for energy storage. According to a survey conducted by the Energy Storage Association, 63% of respondents expected their income to drop due to delayed approval, difficulty in obtaining equipment and materials, and cancellation of customer orders. Moreover, 25% of respondents hoped to reduce their labor force, with the highest reduction rate of 20%. Many respondents believed that despite the enormous economic losses they were facing, they still wanted to retain their employees for the business recovery (Pickerel, 2020).

3.4 Government policies focused on energy security

The energy policy issued by each government is mainly to provide a reliable energy supply to the people. In the context of COVID-19, countries have issued corresponding policies to respond to the pandemic. At present, various countries have formulated short-term policies for the pandemic, and the main target is customers (Qarnain et al., 2021). Both China (Huang et al., 2020) and the United States (KSLA, 2020) have adopted policies that allow late payment without interrupting service. China has also reduced electricity prices, which can help some households and businesses to overcome difficulties while ensuring security of electricity supply. Around the world, most countries have adopted an uninterrupted electricity supply policy to ensure people's livelihoods (Qarnain et al., 2021), especially Indonesia, which has adopted a policy of free electricity for the poor (Harsano, 2020).

On the issue of energy development, the Chinese government introduced policies such as clean energy subsidies, material procurement, and financial support to help the energy industry to overcome various difficulties (Table 2). The focus was on power supply, supply chain, and energy storage in terms of pandemic prevention and control. The United States government also issued related energy development policies after the outbreak. The focus of the policies was to ensure the reliable supply of electricity during the pandemic. Thus, energy infrastructure, such as the power grid received special assistance. Moreover, the Federal Energy Regulatory Commission specifically proposed to give the highest priority to the processing of relevant documents to ensure the reliable operation of energy infrastructure. It can be implied from the comparison that the Chinese government has made a rapid response and formulated relevant policies in response to the impact of COVID-19 on energy, especially the clean energy industry. However, the energy industry support provided by the United States government was limited to the aspect of energy security. It seems that the corresponding support for

Table 2 China's energy policy in response to the outbreak (IN-EN.com, 2020)

Subject	Policy content or objective
Energy storage	Establish energy storage standard system
Renewable energy generation	Reasonably determine the scale of new subsidy projects and optimize the subsidy payment process
Wind energy, photovoltaic	Provide subsidy and enough preparation time
Energy-related material procurement	Take pandemic prevention and control as the main objective, establish green channels for procurement, optimize approval procedures, and ensure procurement quality
Power security	Ensure the power supply service during the pandemic, ensure the power grid's safe operation, ensure the reliable supply of power to users, and properly handle the power production emergencies
Financial support for energy enterprises	Provide preferential financial services and credit support for enterprises greatly affected by the pandemic, and increase the medium- and long-term loan

traditional industries or clean energy was insufficient, leading to some companies applying for bankruptcy, such as Whiting Petroleum, Yuma, Ultra Petroleum, and Freedom Oil, and Gas. The unemployment relief mentioned in Section 3.3 also reflects this view.

3.5 Countermeasures taken against COVID-19

During the outbreak, a reliable energy supply was critical to ensure the normal functioning of people's lives. Therefore, some management and countermeasures were essential. According to a survey, most energy companies responded quickly in the early stages of the outbreak. Their responses were focused on employees, production, and society. Table 3 lists the global responses to COVID-19 in the fields of nuclear energy, oil and gas, and renewable energy. Among the various energy industries, the oil and gas sector actions were outstanding because they had a broader customer base, gave thoughtful consideration to ensure the health of their employees, and made great contributions to customers and communities. Table 4 lists the specific countermeasures of some well-known oil and gas enterprises during the outbreak, including Sinopec in China, and Chevron and ExxonMobil in the United States. Oil and gas enterprises made good use of production advantages during the pandemic, for example, by increasing or modifying production lines to produce numerous pandemic prevention supplies or raw materials.

From the national government level, many

Table 3 Countermeasures of the pandemic in some energy fields

Sector	Response	Content
Nuclear (Pombo-van Zyl, 2020)	Employee	1. Social distancing measures: remote work, shift system, cancel unnecessary business trips, ensure food safety, and exclusive means of transportation
	Production	1. Stop or reduce uranium mining; 2. Replace the main components of the reactor, reduce tasks, reschedule; tasks, and reduce power output; 3. Reduce or stop construction; 4. Close the waste treatment plant
	Society	1. Help with medical supplies and technology
Oil and gas (University of Houston Energy Fellows, 2020)	Employee	1. Strengthen communication between the company and employees; 2. Social distancing measures; 3. Pay attention to the challenges encountered by female employees
	Production	1. Reduce tasks; 2. Reduce or stop construction
	Society	1. Donate; 2. Manufacturing medical products
Renewables (IRENA, 2020a)	Employee	1. Revise labor and education policies; 2. Social distancing measures
	Production	1. Delay project delivery deadline
	Society	1. Provide reliable energy for people's lives

Table 4 Countermeasures taken by Sinopec, Chevron, and ExxonMobil during the outbreak

Aspect	Sinopec (Aikman and Chan, 2020)	Chevron Corporation (2020)	ExxonMobil (2020)
For employee	Provide guidance; more rigorous thermography; scheduling optimization; provide hygiene products; remote work	Provide guidance; more frequent cleaning of the workplace; adjust the layout to maintain social distance; return to work in batches; more rigorous thermography	Restrict business travel; provide guidance; telework; more frequent cleaning of the workplace; adjust the layout to maintain social distance; provide hygiene products
For customer	More frequent gas station cleaning; require customers to wear masks	More frequent gas station cleaning	More frequent gas station cleaning; mobile payment
For community	Donate medical supplies, money, and raw materials for medical supplies; free gas supply to the severely affected areas; produce medical materials and raw materials	Donate medical supplies, money, raw materials for medical supplies, and food; gasoline price discount; produce medical materials and raw materials	Donate medical supplies, money, raw materials for medical supplies, fuel, and food; produce medical materials and raw materials

countries required citizens to be vaccinated in 2021, so that people's lives and economic activities could return to normal more quickly. As of June 28, 2021, a total of 2.9 billion doses of vaccines have been given worldwide. China has administered more than one billion doses, and the United States more than 300 million.

3.6 Academic research focused on energy policy

Since the outbreak of COVID-19, some scholars have also responded. Although there was not much related research, it still provided inspiration and direction for further academic research. Qarnain et al. (2021) reviewed the actions taken by G20 member countries in response to energy consumption during the pandemic. They summarized the policy content and made 11 relevant policy recommendations (Fig. 6). The main recommendations included that the energy sector should ensure a stable supply of energy and grant subsidies to companies that had suffered losses due to the lockdown. Klemeš et al. (2020) put forward the concept of a plastic waste footprint (PWF) in response to the use of massive amounts of plastic products during the period of COVID-19, to facilitate subsequent waste treatment. They proposed that the main waste management challenges after the outbreak included waste classification and treatment. Besides, they pointed out six research directions for the future (Fig. 7). Steffen et al. (2020) put forward challenges and suggestions for the clean energy transition in the short-, medium-, and long-term to help energy policymakers make more reasonable policy plans during the epidemic period and post-epidemic period. Smith (2020) pointed out the problems and challenges that may be encountered in the energy industry's public service. These problems can provide references for managers. Mastropietro et al. (2020) analyzed the energy poverty problem in Italy and Spain in detail and gave ideas and policy suggestions to solve the problem. Graff and Carley (2020) discussed the contradiction between low-income people and the continuous supply of energy. Although it is necessary to ensure the energy security of low-income people, many people cannot pay their energy bills on time. They gave specific data on energy insecurity in the United States and made corresponding policy recommendations. Broto and Kirshner (2020) analyzed the energy needs in daily life, medical services, and the supply chain and concluded that energy was needed to maintain health during the outbreak. Forero-García et al. (2020) discussed the energy-saving strategies of people at home during the outbreak and put forward relevant suggestions. From the above research, it can be concluded that recent research focused on the formulation of relevant energy policies during and after COVID-19.

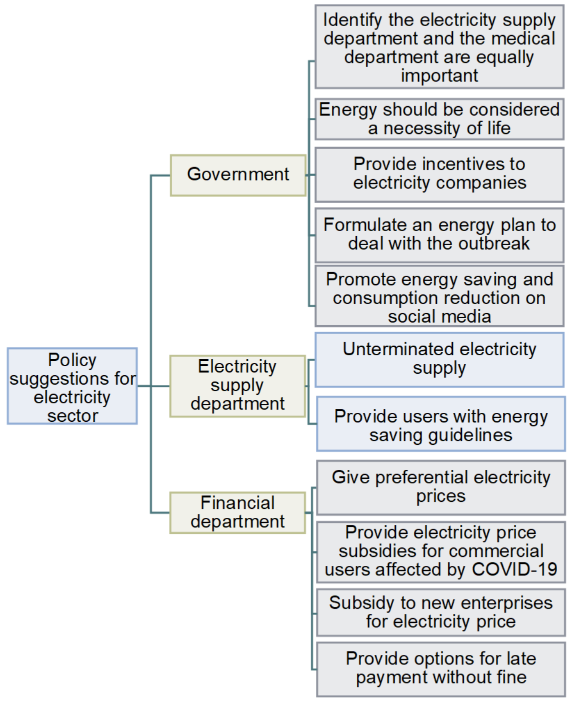

Fig. 6 Policy suggestions for the electricity sector proposed by Qarnain et al. (2021)

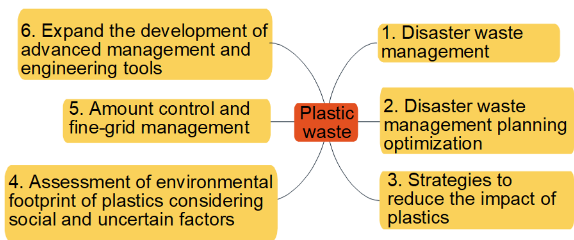

Fig. 7 Six research directions of plastic waste management proposed by Klemeš et al. (2020)

4 Clean energy transition

While responding to the pandemic, how to revive the energy system has become a top priority. Changes in various energy demands during the pandemic revealed that renewable energy was the most resilient energy source after the lockdown. Experts pointed out that it is difficult to carry out energy transition at this time. However, this situation is also an opportunity for the energy sector (IRENA, 2020b). Fig. 8 indicates that, after the pandemic outbreak, the proportion of renewable energy in power generation increased in China and the United States. The proportion of renewable energy power generation increased by about 15% in China, and by about 8% in the United States. According to EIA (2020)'s outlook, renewable energy production will rank third by 2030, and will be the fastest growing source of power generation by 2050. The focus of the energy transition is on clean energy, and its goal is to reduce carbon emissions. Under the influence of the pandemic, although carbon emissions in 2020 Q1 were greatly reduced (by 5% compared to 2019 Q1) (IEA, 2020), experts pointed out that this might not be sustained (Jørgensen and Birol, 2020). Based on the experience of the 2008 financial crisis, carbon emissions in 2009 were reduced by 400 Mt, but carbon emissions in 2010 rebounded by 1.7 Gt (Birol, 2020). Only by achieving a clean energy transition can the structural reduction of carbon emissions be truly achieved. The development focus, challenges, opportunities, and relevant suggestions for clean energy transition are discussed in this section.

4.1 Development focus

4.1.1 Bioenergy

Bioenergy is a renewable energy that is often overlooked and is commonly used for transportation fuels (Berkenwald and le Feuvre, 2020). Although bioenergy accounts for a relatively small proportion of renewable energy and is far behind wind and photovoltaic, it is still a part that cannot be ignored. Europe is the world's largest market for bioenergy,

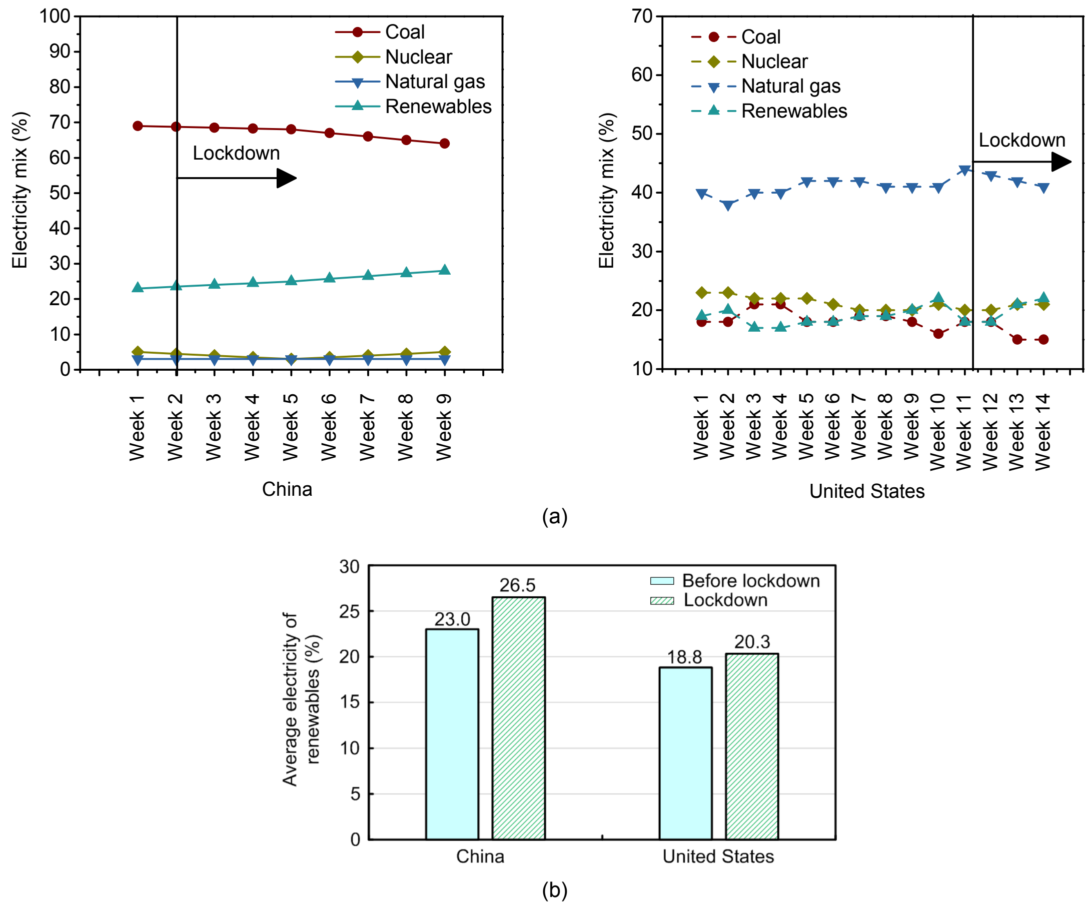

Fig. 8 Electricity mix of China and the United States in the first quarter of 2020: (a) weekly data (data source: IEA (2020)); (b) average values

followed by the United States (EEA, 2018). According to statistics, in 2017, the United States has established more than 450 biomass power plants with a total installed capacity of more than 13 GW. The United States is the world leader in biomass power generation technology and a major producer and consumer of ethanol. In 2017, ethanol production in the United States ranked first in the world, and exceeded that of all other countries combined. China's bioenergy technology started late, but it has developed rapidly in recent years. From the installed capacity of 1.40 GW in 2006 to 14.88 GW in 2017, and it is expected to reach 30 GW by 2030. China's bioenergy is mainly derived from agricultural residues, forestry residues, and garden waste (Fernandez, 2021). At present, the Chinese government is trying to develop bioenergy without competing with edible crops. Therefore, data collection and supply chain management have become necessary in the short- and medium-term.

Bioenergy is also a source of rural economy and employment. According to statistics, in 2018, bioenergy directly or indirectly provided 3.18 million jobs worldwide, including 2 million in biofuels. The liquid biofuel sector provided 311 000 jobs to the United States. The solid biofuel sector provided 186 000 jobs to China, and 79 000 jobs to the United States. Therefore, in the post-epidemic period, bioenergy will play a more critical role in the environment and economy (Voegele, 2019).

4.1.2 Mineral resources for clean energy techniques

Mineral resources are critical raw materials in many clean energy technologies that are widely used, such as electric vehicles, wind turbines, and solar panels. According to rough statistics, clean energy technology usually requires more mineral resources than traditional fossil fuel technology. For example, onshore wind power plants require eight times more mineral resources than gas power plants with the same capacity. With the rapid deployment of clean energy technologies, the demand for mineral resources has increased significantly, and prices have also increased. Thus, the stability of the supply chain of mineral resources is vital in the energy transition (Kim and Karpinski, 2020).

Due to the lockdown caused by COVID-19, the mining industry was halted on a large scale. For example, Peru, which accounts for 12% of the world's copper mines, has stopped mining operations due to the pandemic, and mines in South Africa have been required by the government to reduce production operations. As global demand has fallen, the prices of many mineral resources have also decreased. However, driven by the energy transition, the demand and prices of mineral resources will rise after resuming work. Thus, the mineral resource supply chain's stability has caused the relevant departments to be alert because long-term stable supply is not inevitable.

4.1.3 Battery and electrolyzer

In clean energy technology, batteries and hydrogen-producing electrolyzers play an essential role in economic stimulus (Gül et al., 2020). They are all small and modular technologies, suitable for mass production. Since many countries have introduced relevant policies to encourage the use of electric vehicles, the price of lithium-ion batteries has also been reduced. At present, lithium-ion batteries have gained more opportunities in renewable energy systems. In addition to the transportation field, they are also widely used in integrated power systems (Fig. 9a). The electrolyzer is a low-carbon hydrogen production equipment. Due to its high cleanliness, it is often used in industries where emission reduction is difficult, such as aviation and chemical industries (Fig. 9b). Its advantage is that it can be easily deployed in various fields.

According to the goals set by various countries, the global annual output of electric vehicles will reach 1500 GW·h by 2030. Despite the crisis of COVID-19, this goal has not changed, but it has given a greater driving force. China is a leader in battery production, with 70% of production capacity, followed by the United States with 13%. Although COVID-19 has affected production centers in Hubei, Guangdong, and Hunan Provinces, as these provinces have gradually resumed work, manufacturing capacity has gradually recovered. Europe is the leading producer of electrolyzers. Although production is still in its early stages, production capacity is rapidly expanding. The number of factories producing electrolyzers has increased significantly in recent years, and the production capacity is expanding rapidly. According to statistics, the average capacity of the electrolyzer projects reached 0.64 MW from 2015 to 2019, while the average capacity from 2005 to 2009 was only 0.16 MW. In the next few years, large manufacturing plants in countries such as Norway, Canada, and Japan will be completed and put into production.

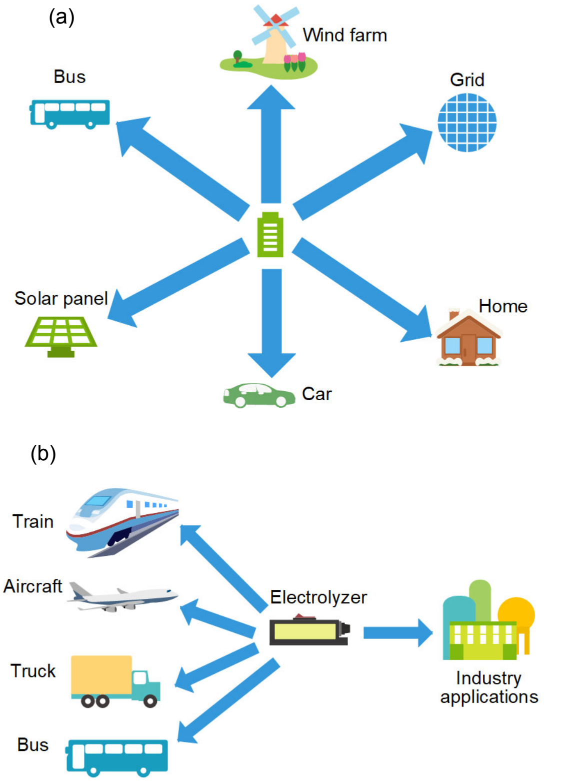

Fig. 9 Application scenarios of batteries (a) and electrolyzers (b)

IEA analysis shows that clean energy technologies and products need to be combined to decarbonize the economy. There is no doubt that electric vehicles will be the most prominent manifestation of the use of battery technology. The cost of batteries accounts for about 40% of the total cost, which will bring huge benefits. Moreover, the deployment of large-scale stationary batteries will make the development of solar power and wind power projects more rapid.

4.2 Challenges

The negative impact of lockdown is already evident. In the clean energy field, due to labor shortages, the delivery of materials, and the installation of new energy facilities have been delayed. Due to the closure of some government agencies, some inspection agencies are unable to approve the license, so even if the construction is completed, it cannot be put into production. As a result of these uncertainties, it will also cause cash flow problems in some supporting businesses and even lead to some investors' insufficient confidence, thus reducing or withdrawing investment. Therefore, the stability of the supply chain is the biggest challenge in the context of COVID-19. The problem of energy supply and demand balance caused by the pandemic is also apparent. During the lockdown, the problem of oversupply became more prominent. At this time, how to store energy is crucial and challenging, especially for the power industry.

For clean energy, there have been supply chain problems for a long time. Driven by COVID-19, these problems have become more serious. Section 4.1.2 has mentioned that some mineral resources are the necessities of clean energy technology. However, due to the uneven distribution of mineral resources on the earth, there are some geopolitical issues, as shown in Table 5. Although the demand for mineral resources is currently reduced due to the pandemic, the demand for mineral resources in the post-epidemic period may rebound significantly driven by the clean energy transition, and the problem of imbalanced supply may occur in the next few years.

Table 5 Challenges of several primary mineral resources (Kim and Karpinski, 2020)

Mineral resource	Challenge	Proportion of production in the world (top 2)
Cobalt	1. Its supply is greatly affected by the nickel and copper markets; 2. Geopolitical restrictions are large, and dependence on a single country is high	1. Democratic Republic of the Congo: 71.4%; 2. Russia: 4.4%
Nickel	1. Geopolitical restrictions are large, and supply security cannot be guaranteed; 2. New investment does not match expected demand	1. Indonesia: 29.6%; 2. Philippines: 15.6%
Copper	1. Depletion of reserves	1. Chile: 27.6%; 2. Peru: 12.3%
Rare earths	1. Geopolitical restrictions are large; 2. Environment pollution in the process is great	1. China: 62.9%; 2. United States: 12.4%

The manufacturing of clean energy equipment has a problem with excessive dependence. For example, Europe and the United States and other countries rely too much on batteries and solar photovoltaic modules from China. Some major Chinese companies provide more than 50% of the supply of solar photovoltaic equipment; China and Europe provide about 60% of the global supply of wind energy equipment.

For governments of all countries, they are now facing tremendous pressure. It is challenging for them to accurately assess its impact on the energy sector due to the uncertainty of COVID-19. From the perspective of clean energy companies and investors, the government's policy is the primary consideration of their decision-making. It has been reported that the behavior of governments is unpredictable. Steffen et al. (2020) put forward that the government can formulate policies in the short-, medium-, and long-term. In short-term policy-making, it is difficult to determine the policy priority that can permanently affect energy transition; in medium-term policy formulation, manage the impact of low interest rates, low oil prices, and economic downturn is hard; in long-term policy-making, predicting possible future turbulence and coordinating policy flexibility and rigidity is challenging.

4.3 Opportunities

Although the clean energy transition is facing severe challenges (Misbrener, 2020), the opportunities coexist. The most significant opportunity is that clean energy can provide numerous jobs. According to the statistics of E2 company, clean energy has provided 3.4 million jobs to the United States in 2019, of which about 60% for energy efficiency, 15% for renewable energy power generation, 7% for new energy vehicles, 4.4% for the construction of clean energy facilities, and 1.2% for biofuels. Although COVID-19 has a major impact on employment in the clean energy field, job demand will rebound in the post-epidemic period. Because COVID-19 made the demand for energy storage more visible, there may be more jobs in the field of energy storage. Globally, renewable energy employed 11 million people in 2018 and may reach 44 million by 2050, while system flexibility and energy efficiency may increase employment opportunities by another 40 million. Thus, its income-generating effect is conceivable. It is estimated that renewable energy can create a gross domestic product (GDP) of 100 trillion US dollars by 2050 (Ambrose, 2020).

On the other hand, the transition of clean energy can make resources better allocated and utilized. For a long time, government subsidies for fossil fuels and coal-fired power have caused a series of problems (Carley and Konisky, 2020). To a certain extent, this has wasted some resources. If these resources can be used for clean energy, it can make the energy system more flexible. Furthermore, environmental pollution caused by fossil fuels makes some people more susceptible to COVID-19. Clean energy can control the deterioration of the environment. In this respect, it brings about an improvement in people's health.

5 Conclusions and lessons learned

This paper reviews the impact of COVID-19 on the energy sector from six aspects and looks forward to what will happen to the energy sector. The focus of the review is the two largest energy countries in the world–China and the United States. The primary findings of the review are as follows:

1. COVID-19 reduced the energy demand globally in 2020 to varying degrees, of which the demand for oil has the highest decline.

2. Due to the lockdown, the pandemic has reduced energy prices to varying degrees and has a huge negative impact on employment, especially for the clean energy industry in the United States.

3. To ensure the electricity supply security, governments of various countries have issued preferential policies for energy consumers, mainly from the aspect of lowering electricity prices and allowing delayed payment.

4. Some energy companies have taken countermeasures to respond to the pandemic from employees, society, and production. Among them, the oil and gas industry has the most outstanding performance in community service.

5. Most scholars' research focuses on energy supply security and policy formulation.

Although the pandemic has negatively affected most aspects of the energy industry, the pace of transition to clean energy has not stopped. This paper describes the focus of clean energy transition from bioenergy, mineral resources, battery, and electrolyzer, and points out the existing challenges and opportunities. The discussions imply that the supply chain stability, electricity storage, and policy formulation are the biggest challenges for the clean energy transition. At the same time, it can bring more opportunities for employment, economic recovery, and the human living environment. Based on the review findings, some lessons have been learned to provide decision-makers with some thinking:

1. Prepare for the unknown: After the outbreak of the pandemic, the Chinese and United States governments have a clear difference in the energy development policy formulation and response speed. Relevant policies should be released as soon as possible after the outbreak. Therefore, the government should design a more flexible policy framework to cope with future crises, and energy security, clean energy development, and employment support should be given priority consideration.

2. Confidence in clean energy: Clean energy is the main body of the future, and it is more flexible than other energy sources during the pandemic. Many companies may have realized that COVID-19 has given them an early look at the shrinking traditional energy sector and the potential for clean energy. Investors should maintain confidence in clean energy because reliable investment is crucial to clean energy development. The government should promote the benefits of clean energy for the economy, employment, and the environment because public opinion is the cornerstone of development.

3. Flexibility in traditional industries: During the outbreak, some oil and gas enterprises made great contributions to the community. They modified the production line to produce all kinds of anti-epidemic products. This shows that although the oil and gas industry belongs to the traditional field, their production capacity and technology are reliable in response to the crisis, and they are more experienced than some emerging industries.

4. Promote the development of the energy storage industry: Energy companies should consider building energy storage facilities. In response to the pandemic, energy storage equipment can be used to adjust the balance between supply and demand, and can be used for peak shaving when the supply exceeds the demand.

5. The priority is to solve the crisis: China has imposed a strict lockdown at the beginning of the outbreak. Although the weekly energy demand reduction rate is very high, the expected annual energy demand reduction rate is very low. It indicates that it is necessary to start a strict lockdown and solve the crisis at the beginning of the pandemic, which can save more lives, and reduce the impact of the pandemic. In addition, the Chinese and United States governments have advocated vaccinating their citizens in the first half of 2021, so that industries can better respond to the epidemic and enable people to return to their original lives faster. It proves once again that when the epidemic arrives, only by guaranteeing people's lives can ensure economic development.

6. Supply chain stability: There are some geopolitical issues in the supply chain of renewable energy, and there are certain dependencies in the manufacture of related products. The government and enterprises should cooperate well to ensure the stability of the supply chain.

7. New management methods: During the outbreak, to maintain social distance, some new management methods (such as remote office and smart factory) emerged and achieved excellent results. On the other hand, some energy companies could not bear the blow of COVID-19 and went bankrupt. Thus, enterprises should pay more attention to the innovation of management mode, digital grafting, and crisis management.

Contributors

Hong-fang LU designed the research. Hong-fang LU and Xin MA processed the corresponding data. Hong-fang LU wrote the first draft of the manuscript. Xin MA helped to organize the manuscript. Min-da MA revised and edited the final version.

Conflict of interest

Hong-fang LU, Xin MA, and Min-da MA declare that they have no conflict of interest.

References

Aikman D, Chan A, 2020. Five Ways Chinese Companies are Responding to Coronavirus. World Economic Forum. http://www.weforum.org/agenda/2020/02/coronavirus-chinese-companies-response/

Al-Saidi M, Hussein H, 2021. The water-energy-food nexus and COVID-19: towards a systematization of impacts and responses. *Science of the Total Environment*, 779:146529. https://doi.org/10.1016/j.scitotenv.2021.146529

Ambrose J, 2020. Here's How Renewable Energy Could Help Us Economically Recover from the Pandemic. Science Alert.

http://www.sciencealert.com/renewable-energy-uptake-could-help-covid-19-recovery-with-100-trillion-over-30-years

Amir M, Khan SZ, 2021. Assessment of renewable energy: status, challenges, COVID-19 impacts, opportunities, and sustainable energy solutions in Africa. *Energy and Built Environment*, in press. https://doi.org/10.1016/j.enbenv.2021.03.002

Berkenwald M, le Feuvre P, 2020. Biofuels in the Time of COVID-19: Staying the Course on Clean Transport Fuels in Latin America. International Energy Agency. http://www.iea.org/commentaries/biofuels-in-the-time-of-covid-19-staying-the-course-on-clean-transport-fuels-in-latin-america

Birol F, 2020. What the 2008 Financial Crisis Can Teach us about Designing Stimulus Packages Today? International Energy Agency. http://www.iea.org/commentaries/what-the-2008-financial-crisis-can-teach-us-about-designing-stimulus-packages-today

Broto VC, Kirshner J, 2020. Energy access is needed to maintain health during pandemics. *Nature Energy*, 5(6): 419-421. https://doi.org/10.1038/s41560-020-0625-6

Carley S, Konisky DM, 2020. The justice and equity implications of the clean energy transition. *Nature Energy*, 5(8): 569-577. https://doi.org/10.1038/s41560-020-0641-6

Cheng E, 2020. Unemployment Ticks Higher in China as Coronavirus Shock to Economy Persists. CNBC. http://www.cnbc.com/2020/05/15/unemployment-rises-in-china-as-coronavirus-shock-to-economy-persists.html

Chevron Corporation, 2020. Chevron's Response to COVID-19. Chevron Corporation. http://www.chevron.com/stories/chevrons-response-to-covid-19-and-market-conditions

Cortiços ND, Duarte CC, 2021. COVID-19: the impact in US high-rise office buildings energy efficiency. *Energy and Buildings*, 249:111180. https://doi.org/10.1016/j.enbuild.2021.111180

Deshwal D, Sangwan P, Dahiya N, 2021. How will COVID-19 impact renewable energy in India? Exploring challenges, lessons and emerging opportunities. *Energy Research & Social Science*, 77:102097. https://doi.org/10.1016/j.erss.2021.102097

EEA (European Environment Agency), 2018. Renewable Energy in Europe—2018 EEA. http://www.eea.europa.eu/publications/renewable-energy-in-europe-2018/

EIA (U.S. Energy Information Administration), 2020. Annual Energy Outlook 2020. EIA. https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf

ExxonMobil, 2020. ExxonMobil and COVID-19. ExxonMobil. http://corporate.exxonmobil.com/News/COVID-19-ExxonMobils-response

Fernandez M, 2021. Biomass Energy in China. Bioenergy Consult. http://www.bioenergyconsult.com/biomass-energy-china/

Forero-García E, Garcia J, Saa-Beltrán P, et al., 2020. Review of energy saving strategies and considerations at the domestic level COVID-19 time. Preprint. https://doi.org/10.13140/RG.2.2.35007.66720

Graff M, Carley S, 2020. COVID-19 assistance needs to target energy insecurity. *Nature Energy*, 5(5):352-354. https://doi.org/10.1038/s41560-020-0620-y

Gül T, Pales AF, Paoli L, 2020. Batteries and Hydrogen Technology: Keys for a Clean Energy Future. International Energy Agency. http://www.iea.org/articles/batteries-and-hydrogen-technology-keys-for-a-clean-energy-future

Haqiqi I, Horeh MB, 2021. Assessment of COVID-19 impacts on U.S. counties using the immediate impact model of local agricultural production (IMLAP). *Agricultural Systems*, 190:103132. https://doi.org/10.1016/j.agsy.2021.103132

Harsano N, 2020. Jokowi Announces Free Electricity, Discounts for Households Hardest Hit by COVID-19 Impacts. The Jakarta Post. http://www.thejakartapost.com/news/2020/03/31/jokowi-announc-es-free-electricity-discounts-for-households-hardest-hit-by-covid-19-impacts.html

Hoang AT, Nižetić S, Olcer AI, et al., 2021. Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: opportunities, challenges, and policy implications. *Energy Policy*, 154: 112322. https://doi.org/10.1016/j.enpol.2021.112322

Huang Y, Lin C, Wang PF, et al., 2020. Saving China from the Coronavirus and Economic Meltdown: Experiences and Lessons. Vox. http://voxeu.org/article/saving-china-coronavirus-and-economic-meltdown-experiences-and-lessons

IEA (International Energy Agency), 2020. Global Energy Review 2020. IEA. http://www.iea.org/reports/global-energy-review-2020

IN-EN.com, 2020. Estimated 5 Billion Yuan! The Ministry of Finance Clarified the Subsidies for Non-water Renewable Energy Power Generation in 2020 (in Chinese). http://www.in-en.com/article/html/energy-2286314.shtml

IRENA (International Renewable Energy Agency), 2020a. Call to Action in Response to COVID-19: Renewable Energy is a Key Part of the Solution. IRENA. http://www.irena.org/-/media/Files/IRENA/Coalition-for-Action/Publication/IRENA_Coalition_COVID-19_response.pdf?la=en&hash=BD7A182A347015C49AF624F1200FEE3667EBF396

IRENA (International Renewable Energy Agency), 2020b. Staying on Course: Renewable Energy in the Time of COVID-19. IRENA. https://www.irena.org/newsroom/pressreleases/2020/Apr/Staying-on-Course-Renewable-Energy-in-the-time-of-COVID19

Jiang P, Fan YV, Klemeš JJ, 2021. Impacts of COVID-19 on energy demand and consumption: challenges, lessons and emerging opportunities. *Applied Energy*, 285:116441. https://doi.org/10.1016/j.apenergy.2021.116441

Jordan P, 2020a. Memorandum: US Energy Employment Initial Impacts from the COVID-19 Economic Crisis, March 2020. BW Research Partnership. http://bwresearch.com/covid/docs/BWResearch_EnergyJobsInitialCOVID-19Memo.pdf

Jordan P, 2020b. Memorandum: Clean Energy Employment Initial Impacts from the COVID-19 Economic Crisis, April 2020. BW Research Partnership. http://bwresearch.com/covid/docs/BWResearch_CleanEnergyJobsCOVID-19Memo_05-13-2020.pdf

Jørgensen D, Birol F, 2020. How Clean Energy Transitions can Help Kick-start Economies. International Energy Agency. http://www.iea.org/commentaries/how-clean-energy-transitions-can-help-kick-start-economies

Kang H, An J, Kim H, et al., 2021. Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea. *Renewable and Sustainable Energy Reviews*, 148:111294. https://doi.org/10.1016/j.rser.2021.111294

Kim TY, Karpinski M, 2020. Clean Energy Progress After the Covid-19 Crisis Will Need Reliable Supplies of Critical Minerals. International Energy Agency. http://www.iea.org/articles/clean-energy-progress-after-the-covid-19-crisis-will-need-reliable-supplies-of-critical-minerals

Klemeš JJ, Fan YV, Tan RR, et al., 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renewable and Sustainable Energy Reviews*, 127:109883. https://doi.org/10.1016/j.rser.2020.109883

KSLA, 2020. Utility customers won't Lose Service During COVID-19 Coronavirus Emergency. KSLA News. http://www.ksla.com/2020/03/16/utility-customers-wont-lose-service-during-covid-coronavirus-emergency/

Mastropietro P, Rodilla P, Batlle C, 2020. Measures to Tackle the Covid-19 Outbreak Impact on Energy Poverty: Preliminary Analysis Based on the Italian and Spanish Experiences. EUI Florence School of Regulation. http://fsr.eui.eu/measures-to-tackle-the-covid-19-outbreak-impact-on-energy-poverty/

Misbrener K, 2020. Report Estimates over half a Million Clean Energy Jobs Will be Lost Through Q2 Without Policy Interventions. Solar Power World. https://www.solarpowerworldonline.com/2020/04/report-estimates-over-a-half-million-clean-energy-jobs-will-be-lost-through-q2/

Narasimha PT, Jena PR, Majhi R, 2021. Impact of COVID-19 on the Indian seaport transportation and maritime supply chain. *Transport Policy*, 110:191-203. https://doi.org/10.1016/j.tranpol.2021.05.011

Petherick A, Kira B, Cameron-Blake E, et al., 2021. Variation in Government Responses to COVID-19. University of Oxford. http://www.bsg.ox.ac.uk/research/publications/variation-government-responses-covid-19

Pickerel K, 2020. Energy Storage Association Survey Finds COVID-19 Will Have Deep, but Brief, Revenue Impacts on Industry. Solar Power World. https://www.solarpowerworldonline.com/2020/04/energy-storage-association-survey-finds-covid-19-will-have-deep-but-brief-revenue-impacts-on-industry/

Pombo-van Zyl N, 2020. Global Nuclear Energy Operations Responding to COVID-19. ESI Africa. https://www.esi-africa.com/industry-sectors/generation/global-nuclear-energy-operations-responding-to-covid-19/

Qarnain SS, Muthuvel S, Bathrinath S, 2021. Review on government action plans to reduce energy consumption in buildings amid COVID-19 pandemic outbreak. *Materials Today: Proceedings*, 45:1264-1268. https://doi.org/10.1016/j.matpr.2020.04.723

Smith DC, 2020. COVID-19 and the energy and natural resources sectors: little room for error. *Journal of Energy & Natural Resources Law*, 38(2):125-129. https://doi.org/10.1080/02646811.2020.1747171

Steffen B, Egli F, Pahle M, et al., 2020. Navigating the clean energy transition in the COVID-19 Crisis. *Joule*, 4(6): 1137-1141. https://doi.org/10.1016/j.joule.2020.04.011

Szczygielski JJ, Brzeszczyński J, Charteris A, et al., 2021. The COVID-19 storm and the energy sector: the impact and role of uncertainty. *Energy Economics*, 105258, in press. https://doi.org/10.1016/j.eneco.2021.105258

U.S. Department of the Treasury, 2020. The CARES Act Works for All Americans. U.S. CARES Act. https://oig.treasury.gov/cares-act

University of Houston Energy Fellows, 2020. Worry and Appreciation: the Energy Workforce Reacts to COVID-19. Forbes. https://www.forbes.com/sites/uhenergy/2020/04/06/worry-and-appreciation-the-energy-workforce-reacts-to-covid-19/#4c7706955c89

University of Oxford, 2020. Coronavirus Government Response Tracker. University of Oxford, UK. https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker

Voegele E, 2019. IRENA: Bioenergy Employed 3.18 Million People Globally in 2018. Biomass Magazine. http://biomassmagazine.com/articles/16307/irena-bioenergy-employed-3-18-million-people-globally-in-2018

Wang Q, Li SY, Jiang F, 2021. 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. *Journal of Cleaner Production*, 313:127897. https://doi.org/10.1016/j.jclepro.2021.127897

Yousaf I, 2021. Risk transmission from the COVID-19 to metals and energy markets. *Resources Policy*, 73:102156. https://doi.org/10.1016/j.resourpol.2021.102156

Zhang LY, Li H, Lee WJ, et al., 2021. COVID-19 and energy: influence mechanisms and research methodologies. *Sustainable Production and Consumption*, 27:2134-2152. https://doi.org/10.1016/j.spc.2021.05.010

Zhang XX, Li ZL, Wang JF, 2021. Impact of COVID-19 pandemic on energy consumption and carbon dioxide emissions in China's transportation sector. *Case Studies in Thermal Engineering*, 26:101091. https://doi.org/10.1016/j.csite.2021.101091