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Impact of COVID-19 on Urban Energy Consumption of Commercial Tourism City

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ABSTRACT

In 2020, the COVID-19 pandemic has spread worldwide. To alleviate this spread, various blockade policies have been implemented in many areas. This has led to a sluggish demand in the world's major economies, sharp drop in the trade index, and negative growth in energy consumption. To formulate a better epidemic prevention policy for urban energy consumption of commercial tourism cities, this study summarizes the major statistics of energy supply and demand before and during the epidemic period based on actual data. The characteristics of energy consumption in different sectors, including hotels, transportation, tourism culture, and public utilities, are then analyzed in detail. Finally, the energy consumption features of commercial tourism cities represented by Macao are compared to those of other typical countries (e.g., Italy, United States, Japan, and Brazil). These analyses demonstrate the impact of COVID-19 on the energy consumption in commercial tourism cities, which provides insights for the government or energy providers to formulate policies to adapt to this pandemic.

1. Introduction

The outbreak of the COVID-19 pandemic in 2020 has affected more than 200 countries and regions. By the end of 2020, the outbreak killed more than 1.8 million people [1]. COVID-19 has a high infectivity and long incubation period, resulting in an exponential growth and waveform expansion of the epidemic. To contain the spread of the virus, many countries and regions have employed unprecedented quarantine measures [2], including closing cities, suspending work, forbidding gathering, and working and studying from home, which changed the human life and production [3,4]. Transportation has a major impact on the energy provision [5,6]. The strict border management and restrictions on traveling abroad implemented by countries worldwide have caused a significant economic depression in air transportation [7]. It has been predicted that the passenger volume has been reduced by 861 million to 1292 million person-times in 2020 [8], which seriously affects the energy consumption characteristics of cities. With the rapid emergence of virtual commerce, education, and social networking platforms, the COVID-19 pandemic has also led to a significant digital transformation. Various uncertainties originated from the epidemic situation have stimulated further exploration of future technologies and significantly increased the combination and innovation of various industries and artificial intelligence (AI) technology in the future [9,10].

Notably, owing to the reductions in most energy demand and global economic activities, the global environment has evidently improved in the short term [11]. Human activities are closely related to air pollution. In recent years, with the introduction of the carbon neutral target, scholars have conducted in-depth research on the issue of virus infection and air pollution. For example, Ref. [12] explored the status of research currently performed concerning the monitoring of SARS-CoV-2 spreading by waste-water based epidemiology and airborne particles. Ref. [13] explored the spread and persistence of SARS-CoV-2 based on particulate carriers. Ref. [14] studied a coherent SARS-CoV-2 air sampling method based on the air quality filter or impactor collection scheme. The reduction in population mobility and industrial production has largely reduced the air pollution and greenhouse gas emissions [15,16], resulting in the highest reduction in carbon emissions in the past decade [17]. The COVID-19 pandemic has a large impact on the short-term social economic development and people's lives, further limiting the consumption demand and export trade dominated by the manufacturing industry [18,19]. Such impacts have resulted in the reduction of electricity demand and brought unprecedented challenges

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to the power industry, which has a supporting role in the development of the human society.

To retard the spread of the epidemic, a city closure policy was implemented, which changed the structure of the energy demand during the epidemic period. As most factories and enterprises are shut down, the decline in industrial and commercial demand has led to a significant downward trend of the overall energy demand of all parts of the world [20,21]. Owing to the implementation of policies such as restrictions on going out, many regions began to implement measures such as work-from-home and remote study, thereby significantly increasing the residential energy consumption [22]. Correspondingly, the change in the energy consumption structure features reshaped the load curves. Affected by the epidemic and traveling restriction policy, people's lifestyles and social modes have largely changed [23]. For example, the proportion of remote working and information sharing in the human life continuously increases. The work from home makes the people's time distribution of energy use more flexible, which causes a time shift in the peak–valley curve [24]. As the peak period of energy consumption shifts back as a whole, the load peak–valley difference between working days and rest days also decreases.

With the change in the energy demand structure, the energy structure on the supply side also changed during the epidemic period. Affected by the COVID-19 pandemic, the overall demand for electricity has declined, resulting in the reduction in thermal power generation and uptrend of multiple distributed renewable energy resource (RES) generations in many regions [25,26]. These trends also reflect the need to explore various cutting-edge technologies for RES, smart grids, and efficient energy storage [27]. Owing to the strong intermittence and volatility of RES [28], the increase in RES utilization will inevitably pose more challenges to power system operation [29]. In addition, the changing characteristics of energy demands also lead to an increase in randomness and uncertainty, which makes the load forecasting more challenging than that in the past. As a result, the economic and secure planning and operation of multi-energy systems face more challenges [30].

Simultaneously, affected by the COVID-19 pandemic, public utilities and enterprises face two major problems, 1) income shrinkage and cash loss caused by the reduced demand and falling prices [31] and 2) increase in the cost of maintaining normal operation of the power system under such specific circumstances [32]. Moreover, because of the problems of reduced demand and supply chain termination, many state-investigated energy projects and plans for new facilities and infrastructure are delayed or shelved, such as the India's RES project [33] and US capacity expansion plan [34]. Various bans had a positive role in reducing urban carbon emissions and improving the environment. However, it is unsustainable and impractical to mitigate the climate change by reducing the human activity. A more effective method is the implementation of clean transformation of energy types [35]. Therefore, it is essential to have a deeper understanding of the changing trend of the power energy industry during the pandemic and analyze the new trend of energy development in the future, which can respond to the needs of countries in terms of climate change, sustainable development, and energy transition.

For commercial tourism cities, whose energy sources usually rely on purchases from adjacent areas, the impact of the COVID-19 outbreak has a higher complexity due to the uniqueness of the economic structure. A better understanding of the energy consumption of commercial tourism cities such as Macao under the epidemic is of significance and can provide a reference for policy makers to formulate better policies. Based on the evolution trend, prevention and control efforts, and resumption of work, this study analyzes the energy consumption of Macao during the epidemic period. It provides a macroscopic analysis of the overall impact of COVID-19 on the Macao's energy. We then analyze the overall situation of the new energy consumption characteristics and carry out a detailed analysis of the impact of the COVID-19 pandemic in different fields (hotels, cultural events, economic events, etc.). In addition, a detailed comparison to the energy characteristics of different countries (Italy, United States, Japan, and Brazil) is performed, which shows the unique characteristics of energy consumption in commercial tourist cities during the epidemic period. Based on the results of the analysis of energy utilization characteristics, this study provides a better reference for the subsequent development of better epidemic control measures and recovery work in commercial tourism cities.

2. Macroanalysis of the COVID-19's Influence on the Commercial Tourism Cities' Energy Consumption

The epidemic prevention and control strategies, energy consumption adjustments, and fluctuations in various industries have brought challenges to the energy industry of commercial tourism cities. The demand and supply structures of power and natural gas, power generation and discharge of power plants, and integrated energy services are directly or indirectly affected. In this section, using the typical commercial tourism city Macao's database as an example, the main performance and changing trend of its energy industry are analyzed.

2.1. Electricity Demand and Supply

As a result of the COVID-19 pandemic, the closure of most sectors of industry, commerce, and tourism has reduced the total power consumption in Macao by 7% year-on-year. Fig. 1 shows the power consumption trends in Macao. As a special administrative region of China, the Macao's power supply originates mainly from mainland China [36]. In addition, the local power generation includes a waste incineration center, natural gas, fuel oil, and photovoltaic power generation. The decline in overall energy consumption during the epidemic period has led to a decrease of 7% in electricity purchases from mainland China. However, owing to the increase in power generation using natural gas, the electricity production of local power plants has increased by 3%. In addition, the Macao's total electricity consumption in the first quarter of 2020 decreased by 20% quarter-on-quarter, with 95.6% of the electricity purchased from mainland China. The electricity generated by local power plants decreased by 95%, including 62.7% from natural gas and 37.3% from fuel oil. The waste incineration center and photovoltaic power generations decreased by 24% and 25%, respectively.

2.2. Natural Gas Demand and Supply

The overall energy consumption characteristics of natural gas are shown in Fig. 2. In the first quarter of 2020, Macao imported 7.43 million m^3 of natural gas, decreased by 88% quarter-on-quarter and increased by 13% year-on-year. In the same quarter, 7.45 million m^3 of natural gas was consumed, of which 46.7% was used for power generation and 53.3% was used for urban gas supply. The Macao's unique geographical environment has vigorously developed the tourism service industry, which is the lifeline of the city's economy [37]. During the epidemic period, the restriction of tourism caused a very large loss of passenger flow in Macao, which significantly reduced the energy consumption of tourism services. In contrast, home offices and remote teaching policies have increased the energy demand in residential areas. Fig. 3 shows the consumption characteristics of the natural gas used for the urban gas supply. In the first quarter of 2020, the gas consumption of the Macao's urban pipeline network decreased by 25% quarter-on-quarter, of which the sales of business and services accounted for 89.1%. Residential gas supplied by gas facility operators accounted for 9.8%, while public welfare gas accounted for 1.2%. The overall consumption decreased by 25% compared to the same quarter last year. Data on the natural gas consumption of several commercial tourism-related customers were collected, including one restaurant and six hotels, to analyze the impact of the COVID-19 epidemic on the tourism industry. The 99^{th} percentiles of the natural gas load consumption of each customer, from January 2018 to July 2020, were

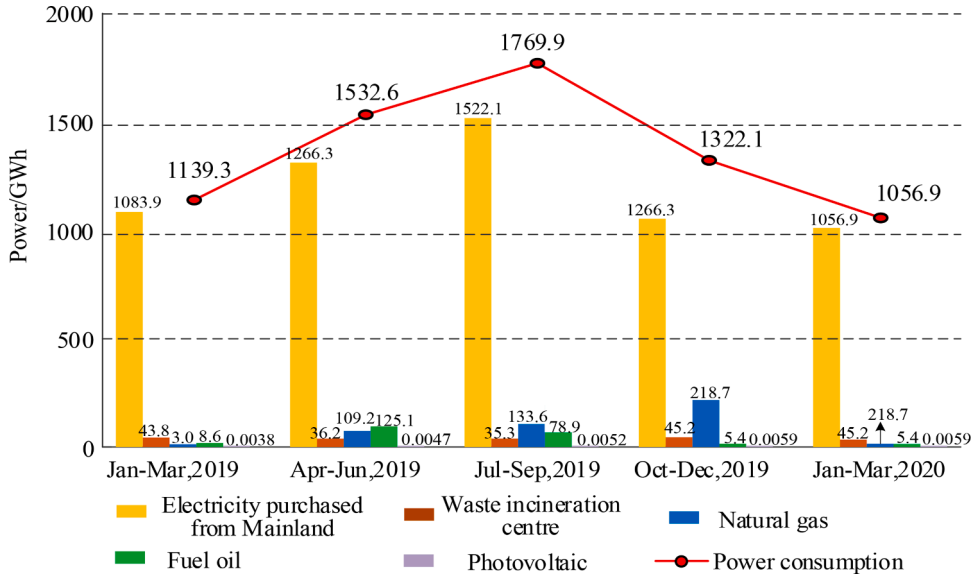

Fig. 1. Power consumption trend in Macao

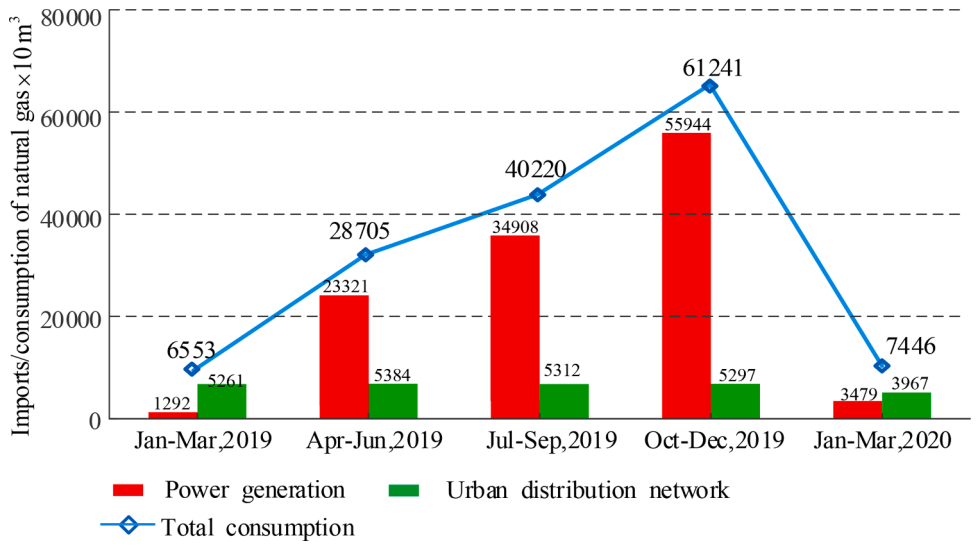

Fig. 2. Overall energy consumption characteristics of natural gas

calculated, which filtered out the abnormal peaks caused by drift and can be regarded as the corresponding customer's maximum simultaneous natural gas load. The coincidence factors (CFs) of each customer, defined by the ratio of each customer's maximum simultaneous natural gas load to the total installed natural gas load capacity were also calculated, as shown in Table 1. The kernel density estimations of the data in 2018, 2019, and 2020, which visualize the distribution of the natural gas load consumption of the two types of customers (restaurant and hotel), and CFs of each customer are also compared in Fig. 4.

As reflected by the 99th percentiles and CFs in Table 1, in most of the scenarios, the actual natural gas load is usually considerably below the installed natural gas load capacity for each customer. The CF of the restaurant is below 0.5, while the CFs of the hotels are below 0.24, from 2018 to 2020. As shown in Fig. 4(a) and 4(b), the gas load levels and CFs of the restaurants and hotels in 2020 were considerably lower than those in 2018 and 2019, resulting in a higher peak in the low-load area. This reduction implies that the business of tourism is bleak during the epidemic period. As the gas load has been reduced under the COVID-19 epidemic, the capacity of the current distribution system has the potential to serve more commercial customers in the future. Instead of upgrading the system in terms of supply capacity, gas suppliers could invest more in the maintenance and intellectualization of the system.

2.3. Power Generation and Discharge of Power Plant

During the epidemic period, the unique energy consumption characteristics and fluctuating loads caused a certain degree of change in the Macao's overall energy supply structure. In order to reduce the spread of the COVID-19 virus, the city has implemented a closed policy. The shutdown of most factories and traffic restrictions largely reduced the emissions of various pollutants. The first outstanding performance was the significant decrease in greenhouse gas emissions, as shown in Fig. 5. In the first quarter of 2020, the carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions from power plants in Macao were reduced by 75% and 43%, respectively. The discharge of biochemical oxygen demand, chemical oxygen demand, and suspended solids in wastewater was evidently reduced. Although the closed policy implemented during the COVID-19 pandemic has reduced urban emissions and effectively

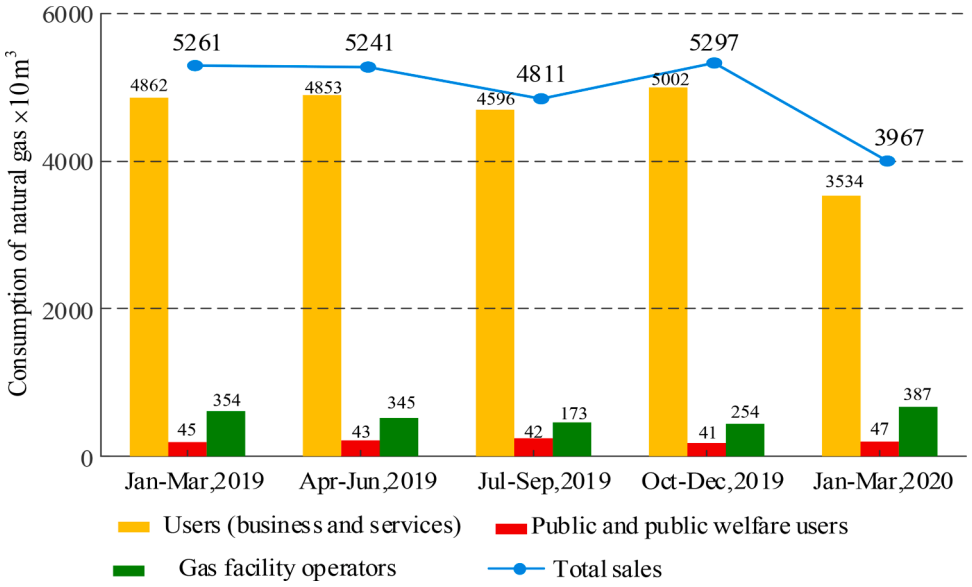

Fig. 3. The consumption characteristic of natural gas used for urban gas supply

Table 1
The installed capacity, 99th percentiles and CFs of the commercial gas loads

Customer	Installed Capacity (m^3/h)	99th percentile of Actual Gas Load (m^3/h)			Coincidence factors		
		2018	2019	2020	2018	2019	2020
Restaurant	41.2	18.2259	19.0115	14.2039	0.4424	0.4614	0.3448
Hotel 1	2211.1	401.6863	343.9133	307.0790	0.1817	0.1555	0.1389
Hotel 2	2572.5	321.1200	303.7600	248.7255	0.1248	0.1181	0.0967
Hotel 3	3219.7	802.1347	752.7692	653.4925	0.2491	0.2338	0.2030
Hotel 4	760.9	103.8752	73.9823	72.9926	0.1365	0.0972	0.0959
Hotel 5	4473.2	943.5000	655.5136	525.4876	0.2109	0.1465	0.1175
Hotel 6	2590.7	531.2900	303.0277	179.7056	0.2051	0.1170	0.0694

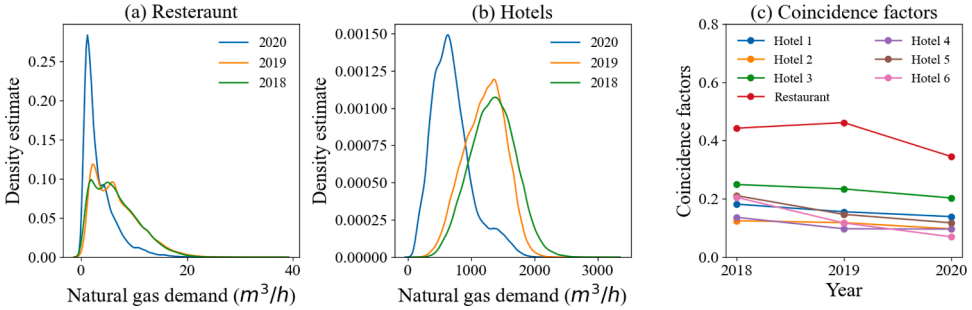

Fig. 4. The kernel density estimation and CFs of the commercial loads

improved the environmental pollution problem. But the closed policy is not a long-term effective method, because long-term closed will hinder the development of human society and economy and violate the development criteria of things. Therefore, long-term air pollution and environmental problems cannot be solved by a closed policy. It should be a rapid transition from clean and low-carbon energy [38], greening and environmental protection, and carbon capture and recycling [39] to achieve effective solutions to environmental problems.

2.4. Average Cost of Electricity

The Macao's average electricity costs in the first and last seasons of 2019 and first season of 2020 are shown in Fig. 6. The cost of electricity purchased in Macao in the first quarter of 2020 was decreased by 4% compared to the first and fourth quarters of 2019. The cost of power generation from oil and natural gas was increased by 46% compared to that of the fourth quarter in 2019. In addition, the costs of power generation from oil and natural gas in Macao were increased by 35% and 28% year-on-year, respectively. Although the cost of electricity generation from oil and natural gas has largely increased, most of the electricity in Macao originates from the purchase from mainland China. Therefore, the overall average cost of electricity in Macao in the first quarter of 2020 was reduced by 2% quarter-on-quarter and 3% year-on-year.

2.5. Power Supply Customer Service

In the short term, the sluggish tourism industry during the epidemic has seriously affected the Macao's overall energy consumption. Some office workers carried out the strategy of working from home, which has

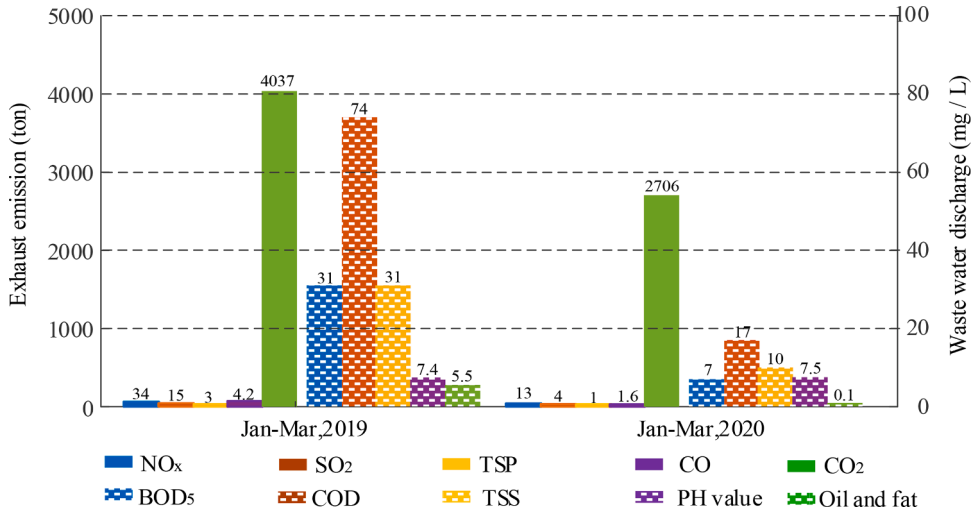

Fig. 5. Discharge of power plant waste

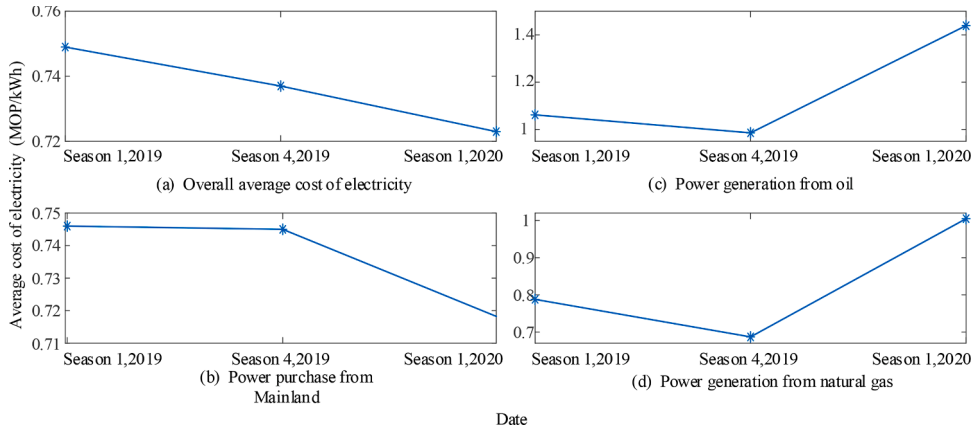

Fig. 6. Macao's electricity costs and investment

led to an increase in residential electricity consumption, while industrial, commercial, and government agencies' energy consumptions largely decreased. Fig. 7 shows the overall electricity sale trend in Macao. By the end of March, there were 268322 electricity customers in Macao, of which the residential and commercial customers accounted for 86.6% and 11.0%, respectively. The overall electricity sales in the first quarter of 2020 were decreased by 18% compared to the previous quarter, of which the commercial users were decreased significantly by

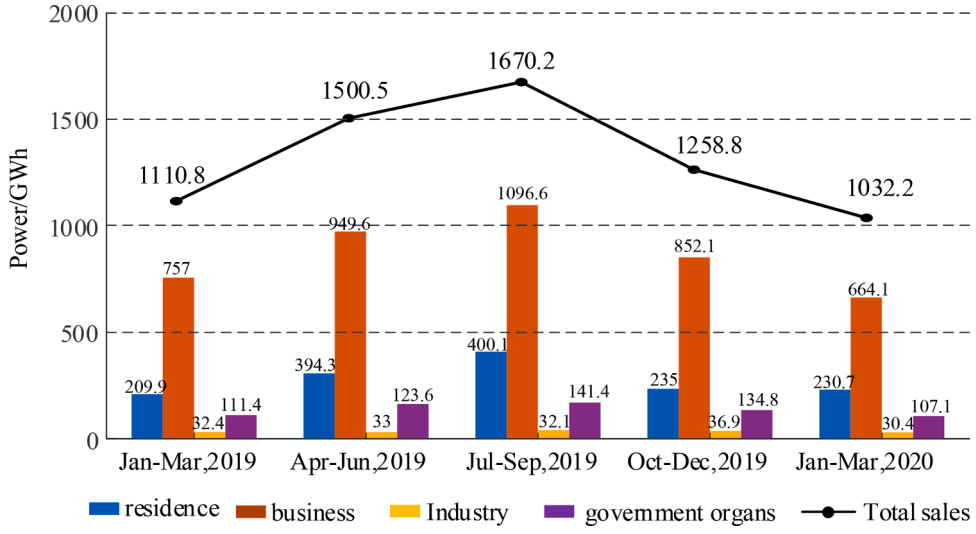

Fig. 7. The overall electricity sales trend in Macao

22%, the residential users were decreased by 2%, and the government agencies and industry users were decreased by 21% and 18%, respectively. In addition, compared to the same quarter last year, the overall electricity sales decreased by 7%, resulting from the decrease in the consumption of all users except residential users.

3. Impact of COVID-19 on Energy Consumption in Different Fields of Commercial Tourism Cities

Since the end of January 2020, the government in Macao imposed restrictions on commercial events, particularly on the lottery industry. On January 27th, people who had traveled to Hubei province in the last 14 days were not allowed to enter casinos, which is recognized as the start of the lockdown in policy aspects. The government furtherly closed most of the indoor entertainment venues on February 4th, including all casinos, cinemas, and game centers. This strict lockdown measure caused a considerable decrease in the electricity demand of the related industries. Such restriction measures were gradually removed in the late February and March owing to the government's quick response and control over the COVID-19 pandemic. The industry began to reopen. However, in April, the revival of the economy was interrupted because of the second outbreak of the epidemic caused by imported cases. Anonymous smart meter data collected by the electricity utility company, Companhia de Electricidade de Macau (CEM), was utilized to investigate the detailed implications of COVID-19 on the electricity demand in different industries. Notably, only a part of the consumed electricity was recorded by smart meters. Thus, the main focuses of this study are the difference in electricity consumption between 2019 and 2020 and the overall trend. Discussion of the numerical amount is not included.

3.1. Energy Consumption Characteristic of Hotels

As shown in Fig. 8(a), in 2020, the electricity demand of hotels (mainly contributed by casino hotels) exhibited a significant decline at the end of January, which is distinctly different from the slowly increasing trend observed in 2019. The decline started on January 24th, immediately after the citywide lockdown was announced in Wuhan. The electricity consumption continued to decrease after the restriction on entering casinos was implemented by the local government. The influence of the second breakout is also reflected in Fig. 8(a), where the blue line dives in early April. At the end of May 2020, the electricity demand recovered to a relatively high level. The distribution of electricity demand in Fig. 9(a) implies that the expectation of electricity demand in 2020 is lower than that in 2019, while the variances are similar. As shown in Fig. 10(a), after the restriction was announced, the peak load from 10:00 a.m. to 10:00 p.m. decreased by approximately 15%. Such decrease leads to a significant reduction in overall electricity consumption and the narrowing of the gap between the peak and the off-peak loads. This is also reflected by the distribution of daily electricity demand in Fig. 11(a), where the peaks of the ridgelines of 2020 shifted to the left after the restriction was announced.

3.2. Energy Consumption Characteristics of Cultural Events

A significant reduction in electricity demand from late January was also observed in cultural events consisting of education, scientific, and recreational activities. The development of remote teaching and online entertainment activities, which was to prevent people from gathering, kept the electricity demand at a relatively low level for approximately three months, as shown in Fig. 8(b). After the restriction was announced, the daily peak demand for cultural events was reduced by more than 20%, which flattened the load curve. After the schools started to reopen from May 4th, the electricity demand gradually increased and exceeded the level before the COVID-19 pandemic. The electricity demand in the first few days in May 2020 was remarkably higher than that in 2019, owing to the cancelation of the Labor Day holiday and preliminary preparation for reopening the campus. As shown in Fig. 9(b), in 2020, the expectation and variance of electricity decreased because of the outbreak of the COVID-19 pandemic. Which might be counter-intuitive is that in Fig. 8(b) and Fig. 10(b), the electricity consumption in 2020 started to decrease before the outbreak of the pandemic, this is because of the earlier advent of the Spring Festival in 2020. Thus, the sharp decrease of the energy consumption, introduced by the restriction measures, is not observed in cultural events, different from observed in hotels. The ridgelines in Fig. 11(b), which show the variance of the distribution of hourly electricity consumption, narrowed in both 2019 and 2020, owing to the influence of the Spring Festival. However, the demand level in 2020 was continuously lower than that in 2019, which reflects the influence of the COVID-19 pandemic.

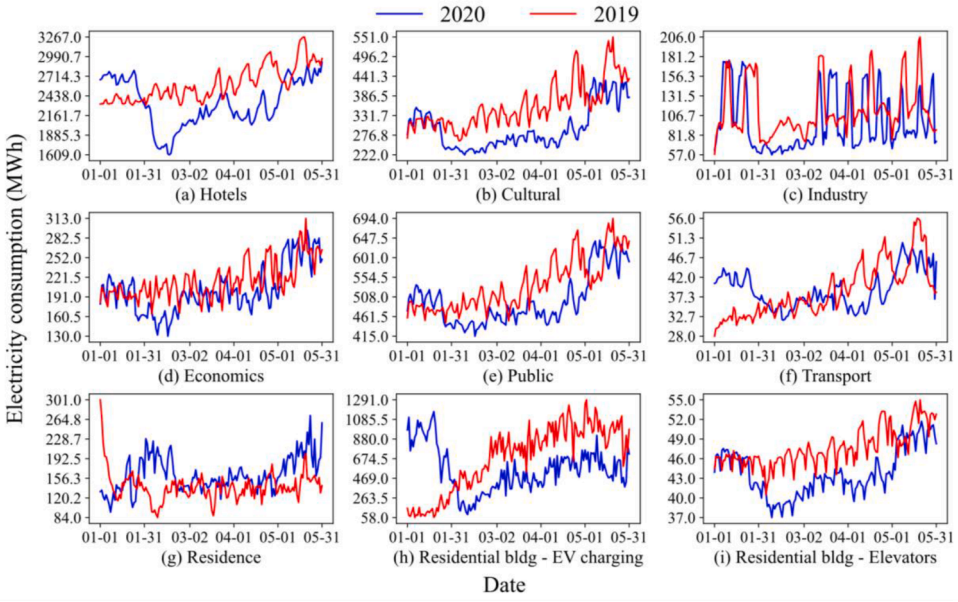

Fig. 8. Daily electricity consumption of different sectors during the first 5 months of 2019 and 2020

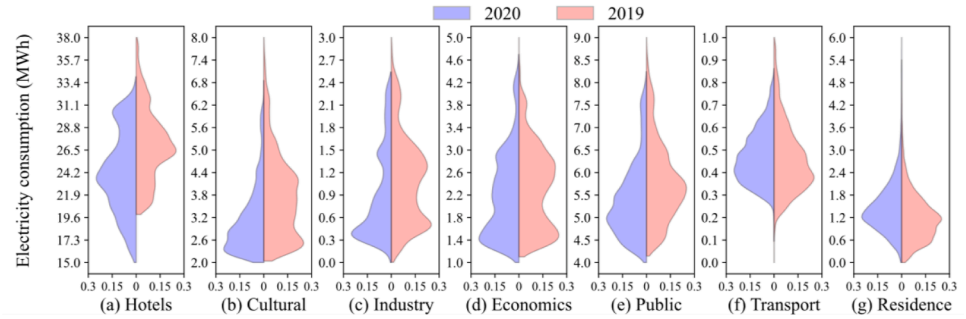

Fig. 9. Distribution of power consumption (15 minutes) of different sectors during the first 5 months of 2019 and 2020

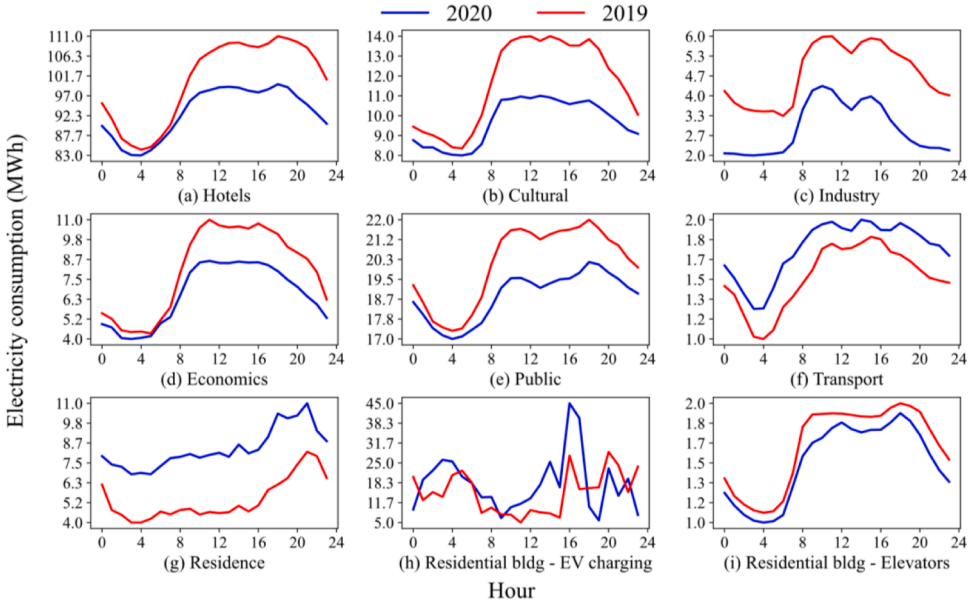

Fig. 10. Hourly average electricity consumption of different sectors, from 27th Jan to 9th Feb in 2019 and 2020

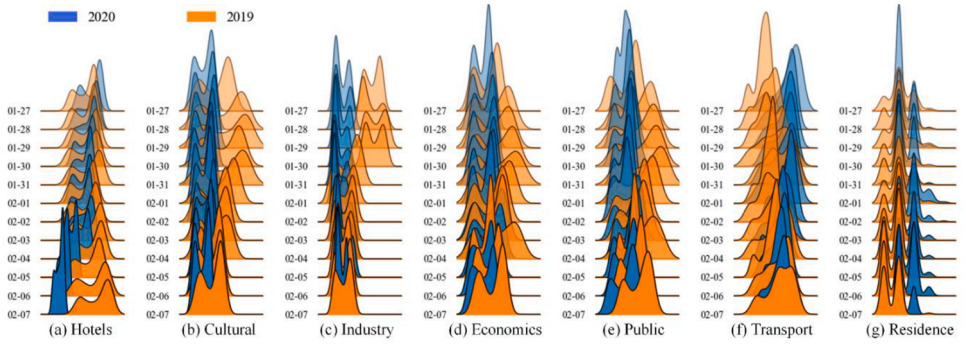

Fig. 11. Daily electricity consumption distribution of different sectors, from 27th Jan to 9th Feb in 2019 and 2020

3.3. Energy Consumption Characteristics of the Industry

The electricity consumption of the industry is not considerably influenced by the pandemic, as the difference between 2019 and 2020 is not as large as those in other fields. As shown in Fig. 8(c), similar to the case of cultural events, the demand started to decrease before the outbreak of the pandemic, due to the arrival of the Spring Festival, which is on February 4, 2019, and January 24, 2020, respectively. However, in 2019, a rising trend appeared soon after the Spring Festival, while the electricity consumption remained low in 2020, owing to the lockdown measures which was introduced to contain the spread of the virus. The electricity demand recovered to its original level in March, but the daily demand in 2020 was slightly lower than that in 2019. According to Fig. 9(c), the maximum demand in 2020 was slightly lower than that in 2019 because of the pandemic, whereas the minimum demand was at the same level. As shown in Fig. 10(c), a reduction in electricity consumption was observed after the restriction was announced, while the depression of the overall demand level in the following two weeks was dominantly determined by the Spring Festival.

3.4. Energy Consumption Characteristics of Economic Events

Here, economic events include commercial buildings and activities, bank operations, and trade. A decrease in electricity demand in 2020 was observed in the two breakouts of COVID-19, at the end of January and the beginning of April. Different form the case of hotels, the reduction in electricity demand was observed before the announcement of restriction measures, which can be explained by the spontaneous behavior of the public to avoid gathering in commercial buildings and banks. This is called a 'bottom-up' response to the COVID-19 pandemic, whereas the case of the hotels, where is dominated by the government policies, is called a 'top-down' response [40]. The influence of the cancelation of the Labor Day holiday on the energy reviving process in May can also be observed in Fig. 8(d). Nevertheless, the overall electricity consumption level in 2020 was similar to that in 2019, resulting in similar electricity demand distributions in Fig. 9(d). However, the impact of the restriction was obvious two weeks after its implementation. The demand in the peak hours was reduced by approximately 30%, while the off-peak demand remained at the same level, as shown in Fig. 10(d) and

3.5. Energy Consumption Characteristics of Administration

The electricity consumption of the public administration exhibits a considerable decrease in late January and remains at a relatively low level until May 2020. This is because the servants in the government followed a strict work-from-home policy after the pandemic broke out, different from the employees who followed turns to work at their offices to minimize the number of people gathering in the working space. Hence, the difference between the electricity demands of 2019 and 2020 was large from January to May. Gradually recovered from the beginning of May 2020, the electricity demand exceeded the level in 2019 in the middle of May and remained at the same level in the following days, resulting from the cancelation of the Labor Day holiday. The continuous depression of electricity consumption is also reflected in Fig. 9(e), which shows that the expectation of electricity demand in 2020 is lower than that in 2019. The demand level decreased after the implementation of the restriction and work-from-home policy, while the load curves of the two years have the same shape, indicating that, although there were fewer staff working in the office, the basic load pattern was not changed by those policies, as shown in Fig. 10(e) and Fig. 11(e).

3.6. Energy Consumption Characteristics of Transportation

At the beginning of 2020, it is worth noting that the electricity consumed by transportation sector was remarkably higher than that in 2019. However, affected by the COVID-19 pandemic breakouts, substantial transportations including flights, ships, and coaches were stopped, resulting in an electricity consumption decrease at the end of January and in early April. Such decrease compensated for the high electricity compensation at the beginning of 2020, therefore the average electricity demand in 2020 is close to that in 2019, as shown in Fig. 9(f). During the pandemic, people prefer to stay at home, which is consistent with observations in the economic sector, resulting in a decrease in electricity consumption after the implementation of the restrictions, as shown in Fig. 10(f) and Fig. 11(f). This can also explain the absence of electricity demand uptrend in 2020, observed in 2019.

3.7. Energy Consumption Characteristic of General Residence

In contrast to other fields, a significant increase in electricity consumption can be observed in residential buildings after the first pandemic outbreak in late January. As shown in Fig. 8(g)–(i), electricity consumption reductions are observed in stairs/elevators and electrical vehicle charging of residential buildings, which are also evidences of the stay-in-home tendency after the restriction measures were announced. This is also supported by Fig. 9(g), Fig. 10(g)–(i), and Fig. 11(g), which indicate that, in a short period after the implementation of the restriction, people tended to stay at home, including working-from-home and going off-duty earlier, resulting in a substantial increase in the electricity demand throughout the day. However, such a situation lasted for only a relatively short period of time, as most of the companies did not apply the work-from-home policy as strictly as implemented by the public administration. As this tendency did not last long, the distribution of electricity demand from January to May in 2020 was similar to that in 2019. Another increase in household electricity demand was observed when the pandemic broke out again in early April. Similar trends were observed in the stairs/elevators and electrical vehicle charging of residential buildings.

3.8. Summary of Energy Consumption Characteristics of Different Sectors

In general, after the COVID-19 pandemic broke out, the electricity consumption changed in different manners in different sectors, indicating the varying response patterns of these sectors. For some of the sectors, for example, hotels and economics, the reaction to the pandemic might appear before the local implementation of the restriction measures. For cities such as Macau, which heavily rely on the tourism industry, the outbreak of the pandemic in neighboring regions impacts the industries related to tourism (e.g., hotels and commercial buildings), regardless of the local policy. This is a spontaneous reaction by the public to avoid infection. The announcement of restrictions by the local government leads to further depression in these industries. The situation improves only when the local restriction is relaxed and the pandemic in the adjacent regions is under control.

Additionally, as the work-from-home policy is always implemented to contain the spread of the virus, the electricity demand in residential areas is likely to increase when the pandemic breaks out. Simultaneously, the electricity demand in offices and transport decreased. The periods of low demand vary across sectors. Although the work-from-home policy was announced after the outbreak, commercial and industrial loads tend to recover as soon as the pandemic is well controlled locally, while the depression of electricity demand lasts longer in the public administration. As observed in Macau, the servants conducted remote working for a significantly longer period than those who worked for enterprises. A similar trend could be observed in education and other cultural events. Students are required to take remote courses until the pandemic is controlled locally and in neighboring regions. Therefore, the electricity demand from educational institutes will be kept at a low level for a longer time period than those in other sectors and is most likely to decrease with the second pandemic outbreak.

4. Energy Consumption Characteristics and Energy Structures of the Commercial Tourism Cities

4.1. Analysis of Energy Consumption Characteristics

The comparison of the electricity consumption data of Italy, United States, Japan, and Brazil from January to May 2019 and 2020 [41] in Fig. 12 shows that, in the COVID-19 pandemic, the implementation of the city closure policy has largely reduced the activities of many large-scale industries and commerce, tourism, and service industries. As a highly developed capitalist country, among the four major European economies, the electricity demand of Italy from March to May 2020 was significantly reduced. The United States, the world's largest superpower, had a downward trend in power demand from January to April. However, compared to April 2020, the electricity consumptions of the two countries in May showed signs of recovery. Owing to factors such as land area, population, and climate, the electricity demand of the United States is not only higher than that of Italy, but also exceeds that of United States in the same month of the previous year [42]. This is attributed to the outbreak of the epidemic with the continuous control of the

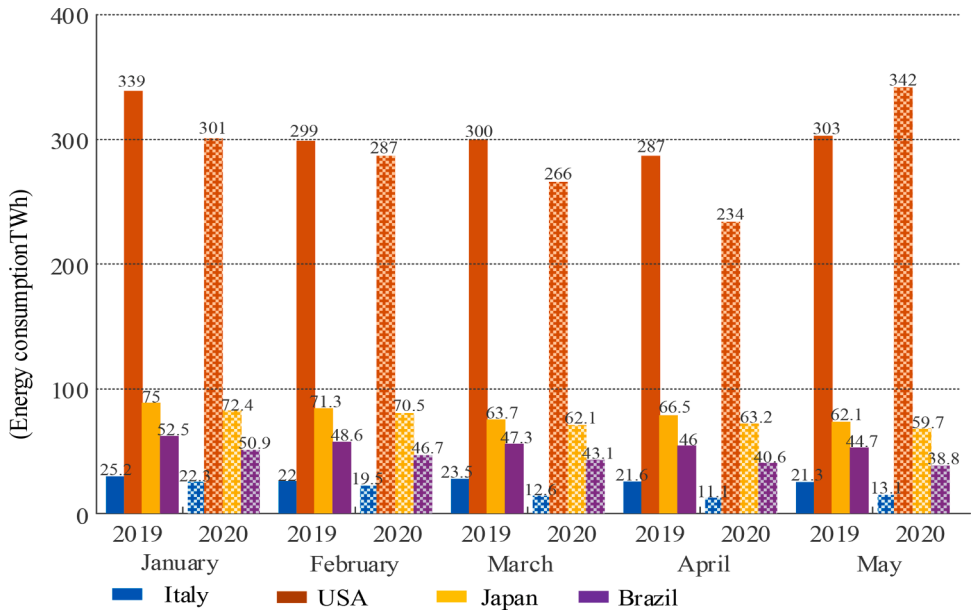

Fig. 12. Energy consumption during epidemic in typical countries

exhibition and gradual implementation of the plan to resume work and production in May. Compared to 2019, Brazil, as the largest developing country in South America, was affected by the epidemic situation. In 2020, its power demand decreased monthly from January to May. The reduction was alleviated in May, which indicates that the Brazil's closed epidemic control policy was eased. However, the data show that the change in electricity demand in Japan was not obvious, which might be determined by the attitude and measures taken by the Japanese government in the face of the epidemic.

Compared to the above analysis of Macao's electricity consumption data, due to urban closure and other reasons, the Macao's electricity consumption trend in the first quarter of 2020 was the same as those of Italy, United States, and Brazil. Under the influence of the COVID-19 pandemic, the overall energy demand exhibited a downward trend under the influence of the pandemic. With the rapid control of the epidemic and gradual implementation of the plan to resume work and production, the power demand began to increase in May. As a city where many world-class casinos are located [43], the economy of Macao relies mainly on tourism, gambling, light industry, and foreign trade [44]. Therefore, the Macao's main energy consumption is also centered around the tourism and service industries. Its commercial power consumption accounts for 64.3% of the total. As one of the most densely populated cities [45], the residential electricity of Macao accounted for 22.3%. Compared to the above-mentioned countries led by industry, owing to the Macao's tourism service industry, the overall energy consumption changes relatively gently under the impact of the pandemic [46]. Owing to the large demand of industrial customers, the shutdown of factories during the epidemic will have a larger impact on the energy consumption characteristics. Compared to large comprehensive cities, the Macao's overall energy use is unique in the following aspects.

Famous entertainment industry

Similar to the Macao's famous gambling industry [47,48], typical commercial and tourism cities have unique entertainment industries. For example, Shanghai, Hong Kong's Disneyland, Madagascar's gaming industry, etc. Electricity, as an important resource, provides power for lighting, air conditioning and various entertainment equipment in various entertainment places in the city [49]. Therefore, the huge power consumption characteristics of the entertainment industry also have a potential and important impact on the energy and power consumption structure of commercial tourism cities [50]. However, affected by the COVID-19 epidemic, many cities have implemented a closed policy in order to curb the spread of the virus, which has had a huge impact on the entertainment industry. The power consumption of the entertainment industry without tourists has dropped sharply, which has caused the overall energy consumption of typical commercial tourism cities to decline and affects the overall structure of energy.

High-quality hotel service industry

As a commercial tourism city, Macao has developed an excellent service industry owing to its unique geographical location and gaming culture [51,52]. In addition, its hotel service industry as a support for the tourism industry is the key to attracting a large number of tourists. Gorgeous hotel architecture and high-quality internal services attract thousands of tourists every year [53]. Owing to its unique operating characteristics and nature of residents, hotel facilities also account for a large part of the overall power consumption of commercial tourism cities. To retard the spread of the COVID-19 pandemic, the hotel service industry has entered the rock bottom, resulting in the reduction in the income and energy consumption of such cities [54]. Moreover, owing to the quarantine measures during the epidemic, some hotels became quarantine areas, offsetting the reduction in electricity consumption.

Rapid development of foreign trade

As a member of the World Trade Organization, Macao maintains good trade relations with many countries and regions, mainly including light industrial products and service trade [55]. With the vigorous development of tourism, the economic status of service trade in commercial tourism cities becomes increasingly important. As a result of the spread of the COVID-19 pandemic, people of more than 200 countries have been infected. This has a very large impact on the global trade and hinders the development of the Macao's foreign trade, and thus seriously affects the Macao's energy consumption characteristics.

4.2. *Analysis of the Power Energy Structure*

According to international energy agency (IEA) data, the share of RESs in the power structure is still large during the COVID-19 pandemic, which does not exclude the regional seasonal climate impact. Owing to the low power demand during the epidemic period, considering the low operating cost of RESs and priority of grid access, the power structure in many countries gradually turns to RESs. Fig. 13 shows the energy structures of several typical countries during the epidemic [56].

In the United States, natural gas is the main source. Owing to the implementation of restrictive measures, RES has contributed

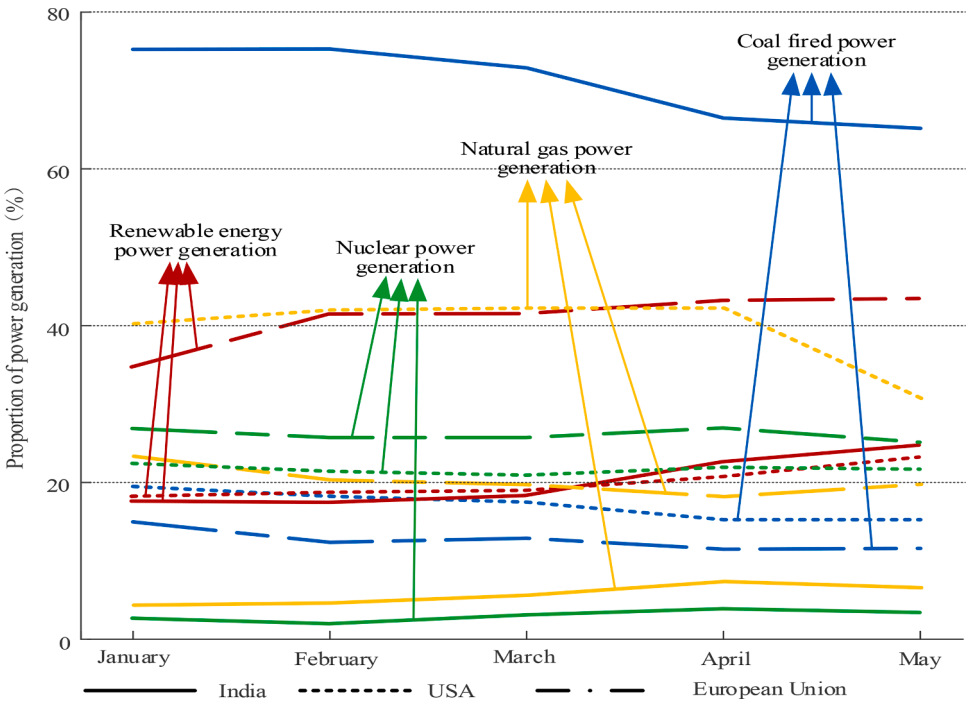

Fig. 13. Energy structure of typical countries

considerably more to the electricity than coal-fired power plants. In March 2020, despite the reduction in seasonal wind power generation and easing of the severity of government anti-epidemic measures, the natural gas continued to dominate. After the implementation of the blockade measures in India, the gap between coal and RES significantly narrowed. The coal remained below 70% of its power structure. At the end of May, the power demand gradually recovered and the share of RES continued to increase. Since the end of June, with the increases in temperature and power demand, the proportion of coal in the power structure has increased while that of the wind energy has declined. This phenomenon occurs because although coal has had a significant impact on environmental pollution, in developing countries, coal, which is more economical, is still the main resource for power generation. In addition, while large-scale volatile new energy sources continue to be connected to the grid, coal-fired power generation can also be used as a flexibly regulated power source to meet the power balance demand in a specific time period and a specific area, thereby effectively solving the problem of system flexibility and resource shortage. Owing to the beneficial weather conditions and geographical location, European Union countries are abundant in renewable resources, such as wind power. Their power generation increased significantly compared to the first quarter of 2019. Affected by the COVID-19 pandemic, the reduction in electricity demand and increase in RES production further deepened the decline in coal and nuclear energy demand. From June to July, the increase in natural gas demand was second, after that in RES. In the case of low nuclear power production, the natural gas compensates for the fluctuation in wind power output every week.

Generally, a commercial tourism city such as Macau is characterized by a dense population and scarce resources [57]. It heavily relies on external resources to meet energy needs. For example, the three major sources of electricity in Macau are local power plants, municipal solid waste incineration power generation, and electricity imported from mainland China [58,59]. Owing to the unique geographic locations of such cities, renewable resources account for only a small proportion of the energy structure. In addition, the development of the tourism service industry has brought a higher potential for waste incineration power generation in commercial tourism cities such as Macao [53]. Generally, the waste incineration power generation capacities of such economic tourism cities are higher than the local natural gas and oil power generation capacities. Therefore, this is also a relatively unique part of the energy structure of such type of city and provides a relatively effective method for the treatment and utilization of the large amount of garbage in modern cities.

5. Conclusion and prospect

In this study, the energy characteristics of the urban energy consumption of a commercial tourism city were analyzed during the COVID-19 pandemic. Based on the Macao's database, this paper expounds the overall macrotrend of energy supply and consumption of commercial tourism cities through comparison with 2019, analyzes in detail the characteristics of energy use in various fields of the city, and compares the energy consumption and structural characteristics of typical countries. This research work has very important practical reference value for energy planning and distribution under extreme natural disasters or major diseases that may occur in the future. The main conclusions of this study are as follows.

Affected by the COVID-19 pandemic, the energy supply and consumption of commercial tourism cities exhibited downward trends. Under the influence of the blockade policy, the decline in energy use has also reduced carbon emissions and improved the environment. However, this kind of energy-saving and emission-reduction measures to restrict human activities and hinder economic development has major drawbacks. Therefore, in order to achieve the long-term goal of carbon reduction, vigorously develop the use of clean and low-carbon energy, and accelerate the transformation of the energy structure are the key measures and technologies to reduce environmental pollution in the future.

The energy consumption of a large number of service industries and public utilities in a typical commercial tourist city has been greatly negatively affected by this epidemic, and it has also caused huge changes in its consumption of electricity and energy, and has a significant impact on the energy structure. Based on this, these special industries with huge potential for energy consumption can be used as flexible adjustment resources for the energy supply of commercial tourism cities. Moreover, these enterprises can further introduce intelligent technology and

intelligent equipment, so as to realize the intelligent response under the adjustment demand of the power supply network.

The comparison of different countries and regions showed that the COVID-19 pandemic has reduced the demand for electricity, while the output of RES has increased. However, because of the characteristics of economic development and geographical resources, the energy structures of most commercial tourist cities in China were still dominated by coal and oil, so that the impact was not obvious. Therefore, developing countries should speed up the improvement of carbon market trading mechanisms, strengthen carbon market supervision, and plan for the exit method and pace of coal power under the new opportunity of promoting carbon neutrality in the world.

In the future, we will further explore the issue of new energy structure transformation in the context of carbon neutrality, and further study and solve the problem of social energy planning and allocation in the emergency of major diseases and disasters.

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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