Spatial and temporal changes in electricity demand regulatory during pandemic periods: The case of COVID-19 in Doha, Qatar

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ABSTRACT

The propagation of the pandemic times, especially during COVID-19, has caused millions of morbidity and mortality cases across the world, forcing people to change their lifestyles and governments to take different measures to slow down the spread of the disease. Consequently, electricity demand and consumption patterns across other socioeconomic sectors were affected by the pandemic. This study aims to investigate the impact of the COVID-19 pandemic on spatiotemporal electricity demand and consumption across six socioeconomic sectors in Doha City, Qatar. The electricity demand and consumption were assessed for three time periods in the pandemic year (pre-lockdown, lockdown, and post-lockdown) compared to electricity consumption prior to the pandemic year (2017–2019). The empirical analysis was performed on a geographically visualized map to determine the areas with high and low electricity consumption. The pattern has been compared before and during the pandemic with previous years. The results show that electricity consumption has increased in the residential and governmental sectors and declined in the industrial and commercial sectors during the lockdown period compared to the post-lockdown period, particularly in the summer season. Mapping the hot/cold spots areas and the temporal analysis of the changing patterns of electricity demand and consumption could provide useful insight to decision-makers for targeted interventions.

1. Introduction

The associated measures during pandemic times applied to contain the propagation of the disease have drastically influenced the patterns of consumer behavior in different applications [1]. The stay-at-home policy imposed by many governments due to pandemic situations has a crucial impact on the energy sector nationally and globally. The stay-at-home policy imposed by many governments due to pandemic situations has created an unprecedented and crucial impact on the environmental and different socioeconomic sectors nationally and globally. Numerous studies have been conducted to investigate the short-run and the long-run effect of the pandemic on the environment, as well as the links between the panandemic and energy consumption [2–9]. For example, Gillingham et al. [5] investigate the short-run and long-run effects of the pandemic on energy and the environment. In the short-run, they found a direct relationship between the decline in CO_2 emissions and air pollutants in the United States and the reduction in the use of jet fuel, gasoline, and electricity demand. On the other hand, they conclude that there will be a significant impact on long-run innovation in clean energy and renewable electricity generation investments. Wang and Su [7] conclude that the pandemic improved air quality in China in the short-run and contributes to a significant reduction in global carbon emissions. However, this improvement is not likely to continue in the long-run as energy use and greenhouse emissions are likely to increase and exceed the levels of the pre-lockdown period. Other studies explored the effects of the COVID-19 pandemic on urban water and the water-energy/electricity nexus [10–16]. Abulibdeh [10] assessed the effect of the pandemic on water-electricity consumption across six socioeconomic sectors. The results show a positive relationship between water and electricity consumption over space and time, ae well as a

functions of different sectors. Roidt et al. [16] studied the sensitivity of the water-electricity nexus in the European electric grid in the context of the pandemic and quantified changes in the blue virtual water trade. They found a direct relationship between the consumptive water footprint of a thermal power plant and electricity demand.

Under the lockdown measures, the electricity consumption behavior in different socioeconomic sectors (i.e., residential, commercial, industrial) witnessed pattern changes, and the reliability of the power system became critical [17–19]. The pandemic's propagation resulted in changes in short-term electricity consumption consistency due to lockdown measures, which increased after easing these measures [10,20, 21]. Furthermore, the reliance on renewable energy resources has increased in many countries, while fossil fuels have been reduced for power generation [22]. However, the impact of the pandemic in the second wave shows that electricity demand is increasing in some sectors and decreasing in others, as many countries are imposing lockdown measures to slow down the propagation of the COVID-19 virus [23]. Therefore, there is a degree of uncertainty related to the severity and impact of these measures on the electricity load profile. There is relatively scarce scholarly work on the impact of the pandemic on spatial electricity consumption across different socioeconomic sectors.

Although the overall electricity consumption in some sectors dropped globally, it created unique repercussions in energy demand. These variations are very complicated in terms of energy types and load profiles. In 16 European countries, the electricity generation from nuclear energy generation and fossil energy generation dropped by 9% (25 GW), 14% (11 GW), and 28% (24 GW) as of April 2020 compared to the mean value from 2015 to 2019, respectively [24,25]. The electricity consumption in China, Germany, India, Spain, France, UK, and Italy during the lockdown in July 2020 witnessed a peak of more than 10% in some sectors compared to the same period of 2019 [23]. In Australia, residential electricity consumption increased by 14% in March 2020 during the lockdown compared with the pre-lockdown period [26].

Different studies have confirmed the redundancy of global electricity demand and consumption during the lockdown; the deterioration, however, was heterogeneous between different socioeconomic sectors. Recent studies have reported that national and international containment measures imposed to control the disease of COVID-19 strongly impacted electricity consumption in many countries worldwide [25,27]. For example [28], conducted a comprehensive review of the impacts and challenges caused by the pandemic on the electricity sector. They concluded that electricity demand decreased globally due to the lockdown and other restriction policies imposed by governments worldwide. On the other hand, the share of renewable generation has increased worldwide. These changes and the uncertainty of electricity demand emphasize greater pressure on power system operators. Ruiz et al. [29] investigated electricity consumption in China and found that it increased due to the lockdown measures taken by the country, particularly imposing the quarantine policy applied by the health authorities. Abu-Rayash and Dincer [30] found that the lockdown policy in Ontario, Canada reduced electricity consumption by 14% and 25% monthly and daily, respectively, during April 2020 compared to the same period in 2019. Moreover, they found that the peak time of electricity consumption during the post-pandemic shifted to the earlier part of the week (Monday to Tuesday) from occurring in the latter part of the week (Wednesday to Friday). This implies that daily peak time dropped as observed in regular morning peak time [31,32]. Werth et al. [25] investigated the effect of lockdown restrictions imposed by 16 European countries on electrical load, generation, and transmission. They found that electricity consumption dropped due to lockdown, making it worthwhile visible to invest in renewable energy generation. Rouleau and Gosselin [33] found that the electricity consumption patterns changed in a Canadian social housing building because of the long lockdown during the first two months of the pandemic. The electricity consumption in residential demand slightly increased; however, the change in the electricity consumption patterns is more pronounced as

the consumption prior to the pandemic was concentrated in the evening period of the day, while during the first two months of the lockdown it was shifted to occur during the whole day. Gillingham et al. [5] found that the overall drop in electricity demand was around 7% from March to June 2020. There was a decline in gas-fired and coal-fired electricity generation by around 20% and 5%, respectively. Edomah and Ndulue [34] investigated the impact of the COVID-19 pandemic on the electricity sector in Nigeria and projected that the share of residential buildings in total building electricity demand increased from 43% under business-as-usual conditions to 49% in a total lockdown scenario. Staying at home policy resulted in changing some households' electricity consumption behavior. In New York, for example, residents reported in a survey that they started using electricity late in the morning due to the lockdown policy compared to prior to imposing this policy and this behavior stayed the same for the rest of the day [31]. It was observed that the energy demand for producing regular products declined, while, on the other hand, it increased when producing medical products and personal protective equipment (PPE) [35].

Research on spatial electricity consumption in different socioeconomic sectors is rare in the literature since the COVID-19 pandemic is a new phenomenon. The electricity load profile is complicated by the impact of the propagation of the disease on different socioeconomic sectors. This study contributes to the literature by investigating the spatiotemporal impacts of the COVID-19 pandemic on electricity consumption in Doha city (Qatar) using electricity consumption readings from different socioeconomic sectors. The electricity data from six different socioeconomic sectors are collected to investigate the difference in electricity consumption during the COVID-19 pandemic in response to the various policies applied to slow down the spread of the virus. These sectors are as follows.

1. *Residential sectors*: Villa and flat data record when the stay-at-home policy was applied to force many people to stay at home.
2. *Commercial, industrial, and hotel sectors:* The data are taken to indicate the impact of the pandemic on economic activities.
3. *Government sector*: It is considered to investigate the impact of the pandemic on the government sector's spatial electricity consumption and how this sector was affected by the pandemic.

This data was combined and divided into three different time periods reflecting the time frame for imposing the lockdown measures as well as the pre- and post-lockdown periods in the year 2020. The monthly load profile data were compared to the same time periods in 2019 to analyze the possible impacts of the pandemic on electricity consumption during the pandemic times. Therefore, this paper aims to analyze the spatial impact of pandemic time (COVID-19 time) on electricity consumption from different socioeconomic sectors. The novelty of this paper is that it presents different approach by studying the spatial impact of the pandemic on the electricity consumption of different sectors.

2. Study area

Doha is the capital city of Qatar, located in the east of the Arabian Peninsula, hosting more than 75% of the total population of the country [36], as shown in Fig. 1. Doha is one of the world's fastest-growing cities [37,38]. Its average annual growth rate reached 6.3% over the last decade [39–41]. Currently, the population of Qatar is about 2.7 million and it is projected to reach about 3.8 million by the year 2050 considering the current growth rate. Over the past few decades, growth in cities and the Gulf Coast associated mainly with hypermodern city development. This was typically the case for Doha, where it was restructured from a small port to a modern global city, following rapid urbanization and westernization. To cater to the rapidly growing population and the increasing demand for both residential and business buildings, Doha has changed with decreased vegetation surfaces and increased built-up areas [39]. According to Ref. [39], an increase of
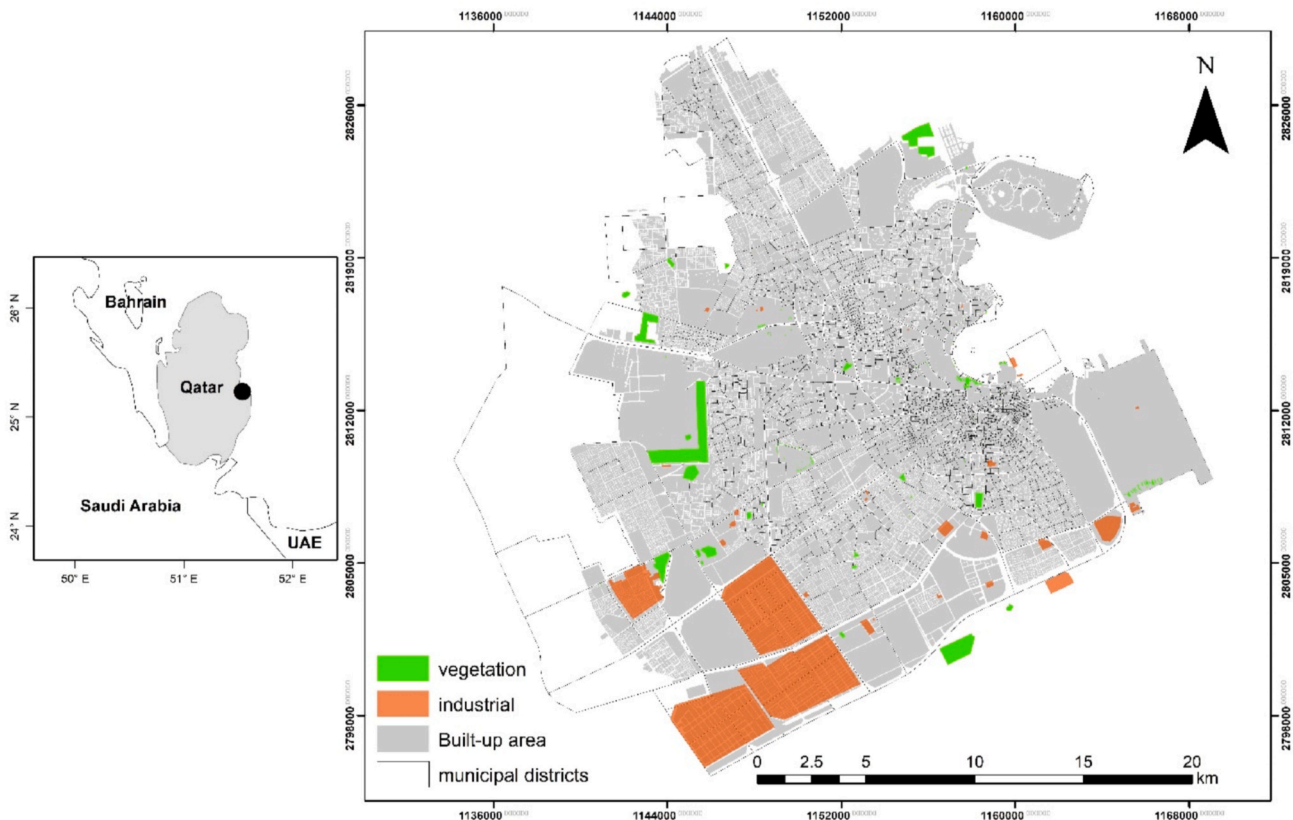
Fig. 1. Location of Doha, its main municipal zones, and dominant land use patterns.

289% in built-up areas occurred in Doha between 1997 and 2010, with more acceleration seen recently to accommodate the 2022 World Cup Competition requirements. This global competition has altered the societal fabric, mainly due to the increased workforce serving the growing city, which has drastically changed the built environment of the city. The climate of Doha is typically hot and dry, following the BWh class according to Koppen's climate classification. The daily average temperature ranges from 14 °C to 22 °C in winter, rising to 31 °C–42 °C in summer [36]. During the period from April to November, the industrial, service, and residential sectors experienced an excessive amount of thermal discomfort, mainly due to the hot and humid climate, leading to an increase in power generation. In addition to the impacts of climate change, energy consumption in Doha is also influenced by population growth, transnational migration flows, domestic growth products, construction activities, industrialization, and international shipping [42].

3. Qatar's electricity load profile

Qatar is categorized as one of the world's high electricity load demand countries and the second-highest electricity consumer among the Gulf Cooperation Council (GCC) nations [43–46]. The income per capita in the country has grown at a rate of 1% during the past few years, while electricity consumption per capita has grown at a rate of 2.6% [47]. The annual electricity consumption rates have increased in the country due to economic development and population growth [48–50]. Between 1985 and 2017, electricity generation increased by 1000%, and the average annual growth of the electricity generation rate was 9.9% between the years 2006 and 2016, and increased by 27.4% in the year 2020 compared to the year 2016 [47]. In the last decade, the electricity demand in Qatar has increased on the order of 7.8%/year, with a peak of electricity demand exceeding 7.8 GW in 2017 [47]. The value of electricity demand in the year 2016, for example, reached a value of 7435 MW, with an increase of 2.3% compared to 2015, and the electricity

transmitted was 39,667 GWH [48]. The highest demand in 2016 was from the industrial sector, with a value of 1560 MW. Fig. 2 shows the monthly electricity generation between the years 2014 and 2020 in GWh. The increase in electricity generation is a response to the increase in electricity demand in different socioeconomic sectors [48]. The figure shows a steady increase in electricity generation since 2014, but a decrease in years 2017 and 2018, mainly due to the conflict between Qatar and its neighbors that took place in June 2017.

The electricity tariff is subsidized for expatriates in Qatar and is free of charge for the country's citizens. This feature puts more pressure on electricity demand, encourages people to consume more electricity, and does not induce energy conservation [47,51,52]. Subsidizing the electricity tariff and the absence of motivation for electricity conservation have led to a high strain on the public budget. The authorities in Qatar are subsidizing the electricity tariffs driven by economic growth and the wealth of oil and gas reservations and exports.

The electricity market tries to fulfill the needs of various socioeconomic sectors of Qatari society and economy and, hence, can be considered a demand-oriented market. Fig. 3 shows the intramonthly cycle of electricity demand in kWh averaged for 2017–2020 for six sectors (residential [villas and flats], commercial, industrial, hotels, and government) in the country. It is illustrated that there is a consistent pattern between these sectors in electricity consumption as the peak of electricity consumption occurs in the summer months (June–September) due to the intensive demand for cooling during hot summers. The industrial and hotel sectors consume the highest amount of electricity compared to the other sectors. Conversely, the flat residential sector consumes the lowest amount of electricity compared to the other sectors. The weather of the country influences the pattern of electricity consumption during wintertime, as the weather is relatively warm, and the consumption is affected by the normal use of appliances, such as water heaters and lightning. The electricity consumption in the summer season is high in all sectors due to extensive use of air conditioning,
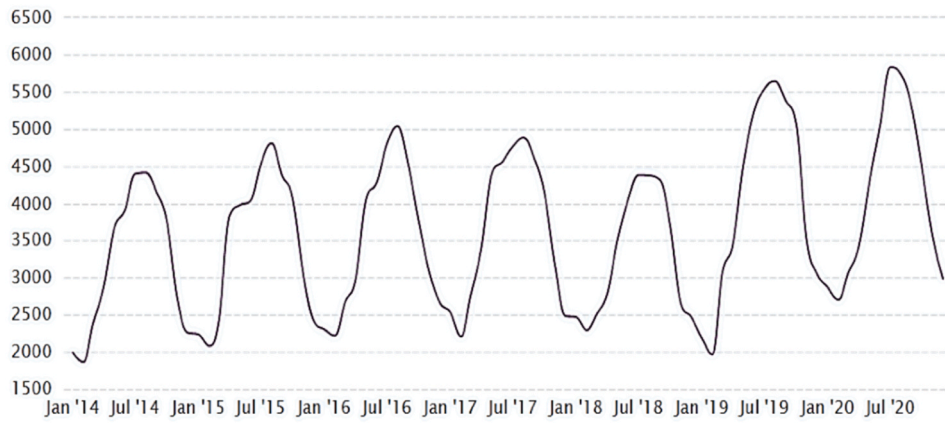
Fig. 2. Monthly electricity generation between 2014 and 2020 in GWh (Source: https://www.ceicdata.com/datapage/en/indicator/qatar/electricity-production).
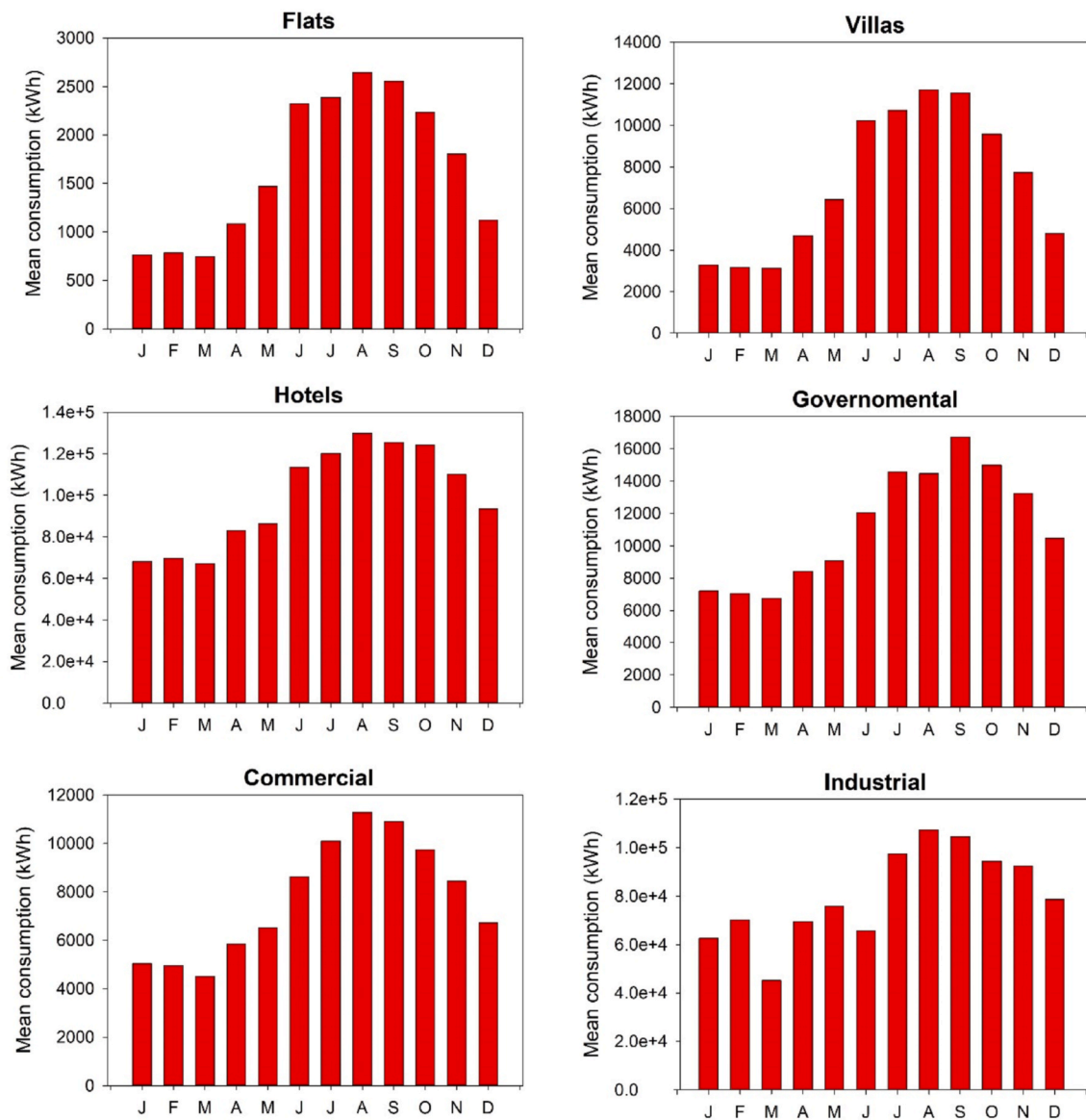

Fig. 3. Intramonthly cycle of electricity demand in kWh averaged for the period 2017–2020.

which is the largest portion of the electricity consumption of the domestic demand since the temperature exceeds 40 °C. As depicted in Fig. 3, the electricity consumption in all sectors, excluding the industrial sector, increased quickly in April due to rising temperature, while decreasing in October due to temperature decline. Furthermore, the electricity demand in the summer season increases by approximately four fold in the residential sector (villas and flats) and by two folds in the other sectors compared to the winter season.

Between 2017 and 2020, the residential sector was the highest electricity consumer in the country and accounted for more than 50% of the total electricity consumption, as shown in Fig. 4. In particular, the residential villas sector was the highest consumer among the six sectors. However, in 2020, the percentage of electricity consumption increased in other sectors, such as the governmental, hotel, and commercial sectors, compared to the period between 2017 and 2019. In 2020, the percentage of electricity consumption had increased in the governmental sector.

4. Datasets and methods

4.1. Dataset description

Data on electricity consumption (kWh) spanning the period from January 2017 to December 2020 were obtained monthly to assess the impacts of mobility restrictions and lockdown measures during the pandemic times (COVID-19) on electricity usage for Doha city. Data were provided at a very detailed spatial scale (i.e., meter level) for five main sectors: residential, commercial, industrial, hotels, and governmental. However, recalling the diversity in residential patterns in this fast-growing city, residential consumption was divided into two subgroups, including villas and flats, as shown in Table 1. We hypothesized that the response of these residential classes can vary considerably in response to the different the lockdown measures. It is worth noting that the monthly electricity consumption data were subjected to rigorous quality control checks to remove meters with missing and zero values in any individual month within the whole study period.

4.2. Methods

4.2.1. Temporal patterns of electricity consumption

The anomalies were computed based on the temporal sequence of the period 2017–2020 to assess the possible influence of the COVID-19 pandemic on electricity consumption. Moreover, the relative changes were computed in percentage for the electricity consumption during each month of 2020, then compared to the consumption averaged for the same month during the preceding three years (i.e., 2017–2019). Temporal anomalies were computed for each meter in the city, as well as for each sector. This analysis gives indications of changes in consumption trends under different conditions: i.e., pre-lockdown (i.e. January–March), lockdown (i.e. April–June), and post-lockdown (July–December) periods. Also, this analysis allowed for determining the different profiles of consumption across various sectors and districts in the city. Herein, the temporal anomaly (Consumption anomaly) for each meter (i) within a particular month (t) was computed as in equation (1):

$$100*\left(\frac{C_{ti}^{2020} - C_{ti}^{2017-2019}}{C_{ti}^{2017-2019}}\right) \qquad (1)$$

where C_{ti}^{2020} is electricity demand for the month (t) in 2020, and $C_{ti}^{2017-2019}$ is the average demand for the same month over the period 2017–2019. According to equation (1), the obtained anomaly can be either positive or negative, suggesting increasing or decreasing trends in electricity consumption, respectively. The anomaly refers to "stable", when the anomaly equals zero. Recalling that the data are available on a monthly time scale and for a short time span (4 years), it was not possible to provide a "robust" analysis of the statistical significance of the obtained differences during 2020 and earlier years.

4.2.2. Spatial patterns of electricity consumption

The data is collected from the local authority and analyzed, as shown in Fig. 5. The data screening was conducted for quality control and reconstructed to ensure the same unit with the same ID is monitored in all years (2017–2020). The spatial data are divided based on load types: residential, commercial, governmental, and industrial sectors, including flats, villas, hotels, commercial buildings, governmental buildings, and manufacturers. Moreover, a hotspot analysis was used within a GIS
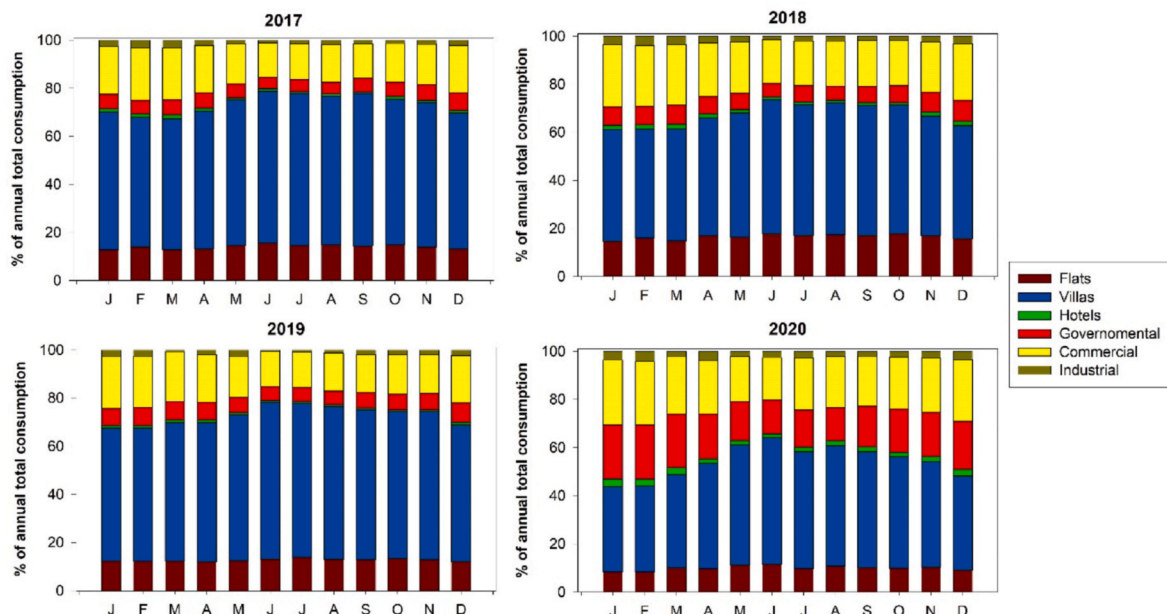

Fig. 4. The relative contribution of the different sectors to the annual electricity consumption in Doha from 2017 to 2020.

Table 1
Description of the socioeconomic sectors and related hypotheses of water and energy consumption.

Socioeconomic sector	Description	Number of readings (%)	Rational
Residential	Villas	118,934.	Villas, in general, are found in two types in Doha, Qatar. The first one is composed of villas that are found in compounds for expat families. These villas may take the shape of townhouses. The second type is standalone villas, which are preferred and mainly occupied by Qatari nationals. Large families usually prefer villas due to their large areas. The residential sector is one of the major sectors that consume electricity. The lockdown policy forced many people to work or learn from their houses and, hence, this policy may have some impact on the pattern of electricity consumption.
Residential	Flat	106,970	This type of building is the most popular among the expat residents of the country. They are available in different sizes and shapes. The majority of these buildings are located in Doha city.
Commercial	Banks, services institutions, SMEs, private organizations, retail, groceries and pharmacies, etc.	46,415	This sector is spread throughout the city. This sector was negatively affected by the lockdown measures since they were ordered to close to prevent the spread of the disease.
Industrial	Liquefied natural gas, crude oil production and refining, ammonia, fertilizers, petrochemicals, steel reinforcing bars, cement, commercial ships, repairs	590	The industrial sector consumes a high amount of electricity. This sector was affected by the lockdown policy and hence impacted the pattern of electricity consumption. The industrial area is located in the southern part of Doha city.
Government	Ministries, public schools, offices, hospitals, and universities, etc.	15,551	Government institutions are concentrated in Doha city. During the lockdown period, only 20% of the employees were working from the offices and the rest

Table 1 (*continued*)

Socioeconomic sector	Description	Number of readings (%)	Rational
			were teleworking. Students started online learning, but hospitals increased their capacity to receive more patients.
Hotels	Hotels and service apartments	1450	The occupancy of the hotels depends on tourists, and tourism to Qatar was negatively affected by the pandemic. However, many of these hotels were used for quarantine purposes for those traveling to the country.

environment to investigate the spatial patterns of electricity consumption during the pre-lockdown, lockdown, and post-lockdown periods. The Getis-Ord Gi* statistic, as summarized by z-score and p-values, was used to identify areas of unusually high and low consumption for each period. Within a GIS environment, a hotspot analysis was implemented, which uses data vectors to locate statistically significant hot and cold spots in data structure by combining or converging points that are close to one another (i.e. spatially autocorrelated). The analysis clusters features with similar high (hot) or low (cold) values (electricity consumption in our case) [53]. Specifically, the Getis-Ord Gi* statistic was used to determine the shortest distance between every neighboring unit in order to quantify how far the values of a certain variable are located spatially. A Z-score indicates how strongly clustered the data is, while a p-value indicates how probable the spatial pattern observed was formed by chance. The feature is deemed to be part of a hotspot when its value is positive and all of its nearby features' values are similarly high. On the other hand, a statistically significant Z-score is obtained when the local sum differs significantly from the expected local sum, and the difference is too high to be due to chance. The statistical significance of the identified clusters (i.e. hotspots and cold spots) was examined at three different levels: 99%, 95%, and 90%. The higher the Z-score for statistically significant positive, the more intensive the clustering of high values. As a result, hotspots are usually indicated by clusters of high positive Z-scores, while clusters of high negative Z-scores usually indicate cold spots. Following the results of the Getis-Ord Gi* values and their significance levels, the city of Doha was divided into three primary sections: hotspots, cold spots, and non-significant clustering zones. The estimated heat and cold areas are designed for three separate periods in both 2019 and 2020: before the lockdown (January–March), during the lockdown (April–June), and after the lockdown (July–December). The G* coefficient was calculated according to Getis and Aldstadt (2004), as in equation (2).

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{s \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{2}$$

where N is the number of locations in the city, X_i is the variable value at a particular location, X_j is the variable value at another location, X is the mean of the variable, and W_{ij} is the weight applied to the comparison between location i and location j. This distance-based weight matrix is based on the inverse distance between locations i and j (i.e. $1/d_{ij}$). Hotspot analysis has been widely used in the literature to investigate the
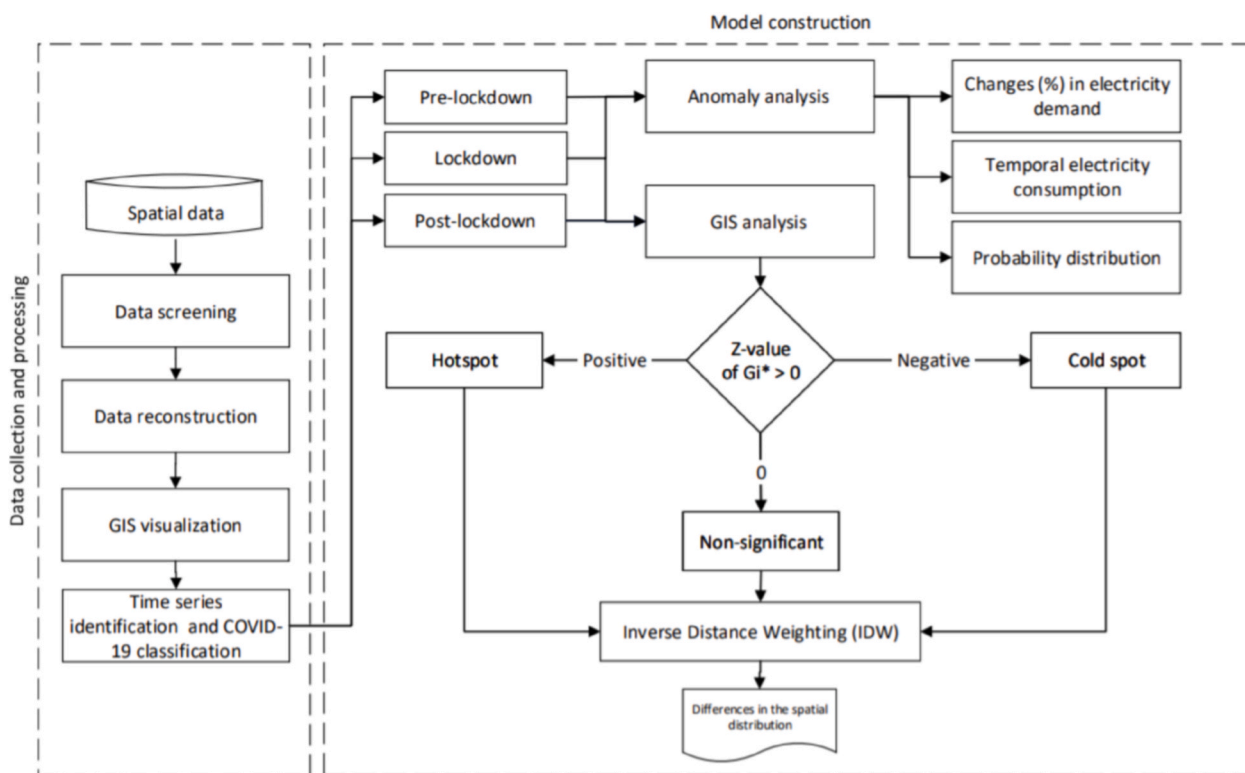
Model construction

Fig. 5. The data collection and processing with model construction.

spatial patterns of various phenomena, such as ecosystem services (e.g. Zheng et al., 2016), soil erosion (e.g. Mekonnen and Melesse, 2011), flooding areas (e.g. Majumder et al., 2019), road traffic accidents (e.g. Zahran et al., 2019), and crime mapping (Mohammed and Baiee, 2020).

The Getis-Ord Gi* values were interpolated to turn discrete point data into continuous density surfaces using the inverse distance weighting (IDW) interpolation method. This process creates a raster file that shows areas with high and low cluster accident rates. The IDW is a frequently used spatial interpolator that uses linear-weighted sample points to generate cell values. The interpolated value is weighted depending on the location of the points (Yang et al., 2020).

5. Results

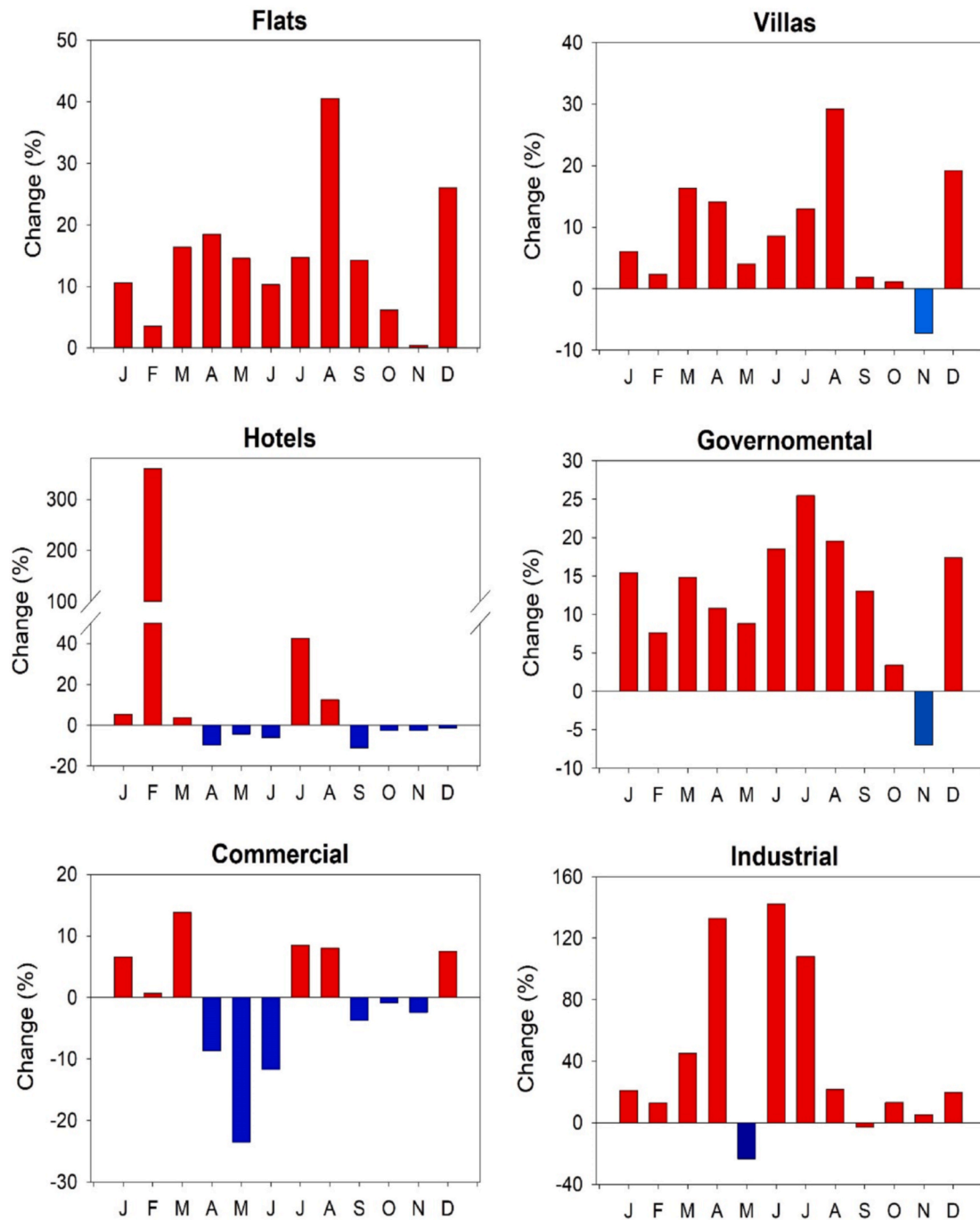### 5.1. Temporal evolution of electricity consumption

The percent changes in the monthly electricity demand for the six sectors in the pandemic year (2020) were computed with respect to the average for the same month over the 2017–2019 period, as shown in Fig. 6. This study aims to determine whether electricity consumption increased or decreased during the pandemic year for which sectors and in which months. This could indicate if the propagation of the COVID-19 pandemic affected electricity demand and consumption. Also, to determine if the associated measures imposed to slow down the spread of the disease affected the demand for electricity in some sectors. A substantial increase in the residential sector, both in flats and villas, can be noted. A few interesting observations can be made about changes in the electricity demand in the residential sector. First, there is a substantial increase in the months of March and April at the beginning of the spread of the disease and imposing the lockdown measure. Another significant increase in electricity demand occurred in August due to the ban on international travel. Hence, Qataris and expats stayed in the country and increased the demand for electricity during the hot summer season and the intensive use of air conditioning for cooling. The figure shows that the demand for electricity increased slightly in November for residential

flats but decreased in the residential villa sector. The reason behind this decrease might be related to other than COVID-19, as at this month the lockdown policy was lifted completely. The governmental sector witnessed a substantial increase in electricity demand, particularly in the summer season. This increase reflects the natural growth in this sector and the increase in occupation rates. In the summer, many employees were unable to take their vacation leave and, hence, the occupation of the buildings increased compared to the same period between 2017 and 2019, which resulted in an increase in electricity demand in the governmental buildings.

Looking at the hotel sector, the figure shows a significant increase in electricity demand in February. This can be attributed to the natural increase in the number of hotels in the city and the tourism activity at this time, when the weather is moderate and the tourism season is at its peak. However, in the following months (April, May, June), the electricity demand decreased substantially in this sector because of the lockdown policy. The tourism industry was negatively affected globally and many countries, including Qatar, imposed restrictions on international flights and people's movement nationally and internationally. In July and August, the electricity demand increased in the hotel sector as the government used these hotels as quarantines for those traveling to the country.

Furthermore, the electricity demand is elevated in these two months as they are the hottest months in the summer season, and there is a high demand for air conditioning. The electricity demand decreased between September and December due to the restrictions on tourists entering the country. Similarly, the commercial sector witnessed a substantial decrease in electricity demand between April and June, mainly due to the lockdown during the pandemic. The electricity demand also decreased between September and November, suggesting that this sector has not recovered completely from the impact of the pandemic. Finally, the industrial sector witnessed a substantial increase in electricity demand in the early months of the year but a significant decrease during the month of May throughout the lockdown period.

Analyzing the temporal evolution of the monthly electricity

Fig. 6. Changes (%) in electricity demand during the months of 2020, as a function of the different land use types. Changes were computed with respect to the average for the same month over the 2017–2019 period.

consumption from January 2017 to December 2020 for the six socio-economic sectors (as shown in Fig. 7), illustrated the impact of the pandemic on the electricity load profile during the pandemic year (2020), considering the natural increase in electricity consumption due to population and economic growth. As illustrated, the temporal evolution of electricity consumption for each sector from January 2017 to December 2020. The anomalies were computed for each month independently with respect to the consumption for the same month between the years 2017 and 2019. The rationale is to explore whether electricity consumption during the different periods of 2020 (i.e., pre-lockdown, lockdown, and post-lockdown) was different from that for the corresponding period from 2017 to 2019. As depicted, for flat consumption,

an anomalous high consumption was noted in the post-lockdown period in 2020, as August and December witnessed a remarkable increase in electricity demand on the order of 218.34 and 175.04 kWh, respectively, compared to the corresponding months between 2017 and 2019. Notably, the flat consumption in August 2020 exhibited the highest increase over the whole study period. An inspection of electricity consumption for the flats sector demonstrates that the consumption increased during the early lockdown period (i.e., late March and April 2020), respectively, compared to the average consumption for these two months before 2020. A drastic decline in flat consumption was noted after the lockdown period, mainly in September (−85.6 kWh), October (−112.17 kWh) and November (−42.21 kWh). As another residential
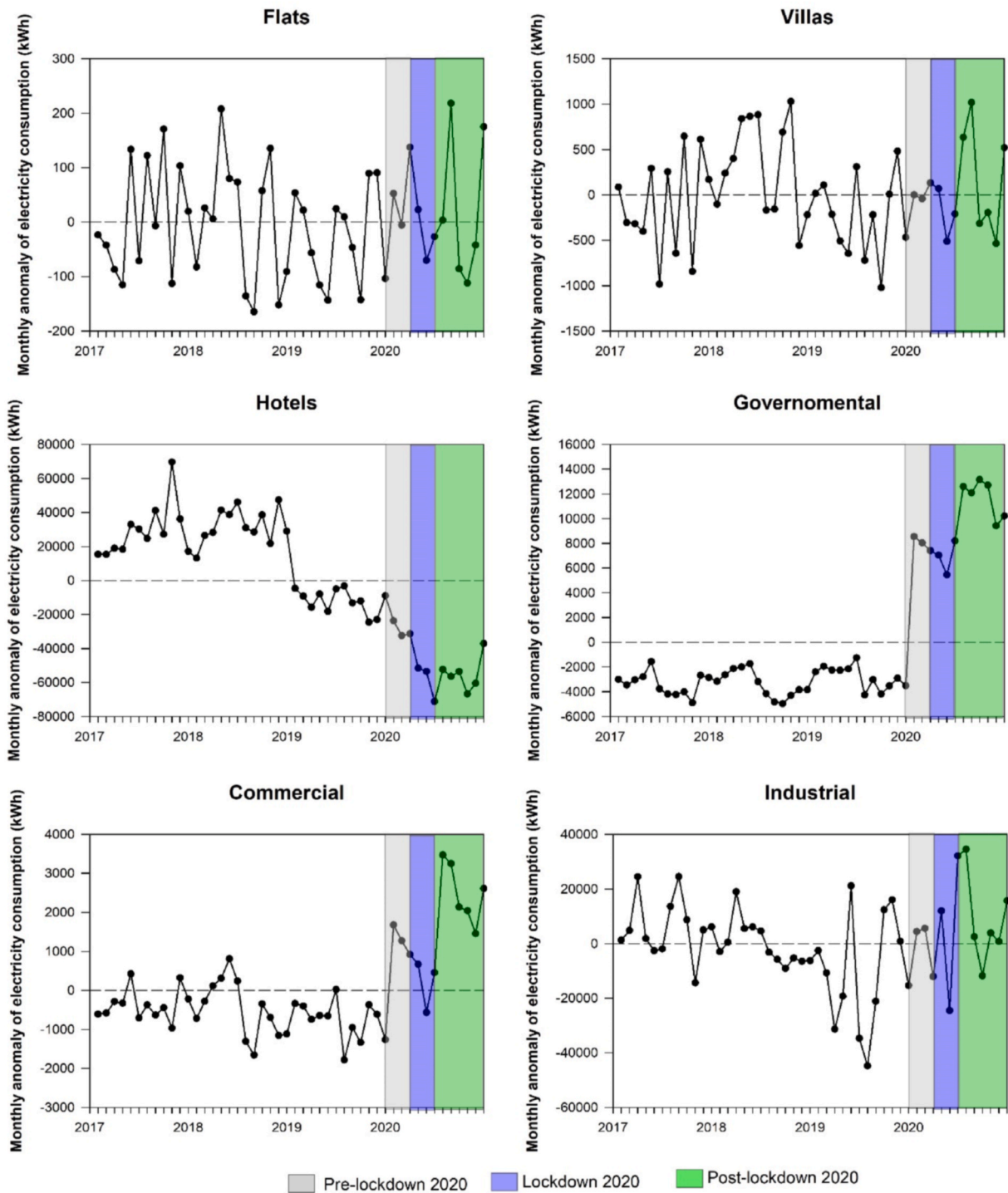
Fig. 7. Temporal evolution of the monthly electricity consumption from January 2017 to December 2020. Anomalies were computed for each month independently, with respect to the average of the period 2017–2020.

land use pattern, it was noticed that the temporal evolution of electricity consumption for villas showed a similar pattern to flat consumption in 2020. Specifically, a substantial increase in consumption was observed in the post-lockdown period, mainly in August (1019.48 kWh) and December (519.99 kWh). Rather, the drop in consumption was during the fall months of the post lockdown period (i.e., from September to November). Again, the early period of the lockdown (late March and April) showed a positive anomaly in electricity consumption in villas, which is revered during the late period of the lockdown (May and June). Likewise, in flats, the electricity consumption in villas was exceptional in

August 2020, relative to the whole study period. An inspection of Fig. 6 reveals that electricity consumption showed a considerable change in its pattern after 2020, when there was a significant increase in the consumption of the governmental and commercial sectors, while hotels exhibited a significant decrease. Nonetheless, despite this anomalous increase, a comparison of the consumption trends for these sectors in 2020 shows that the consumption was much lower during the lockdown period (April–June) compared to the pre-lockdown (January–March) and post-lockdown (July–December).

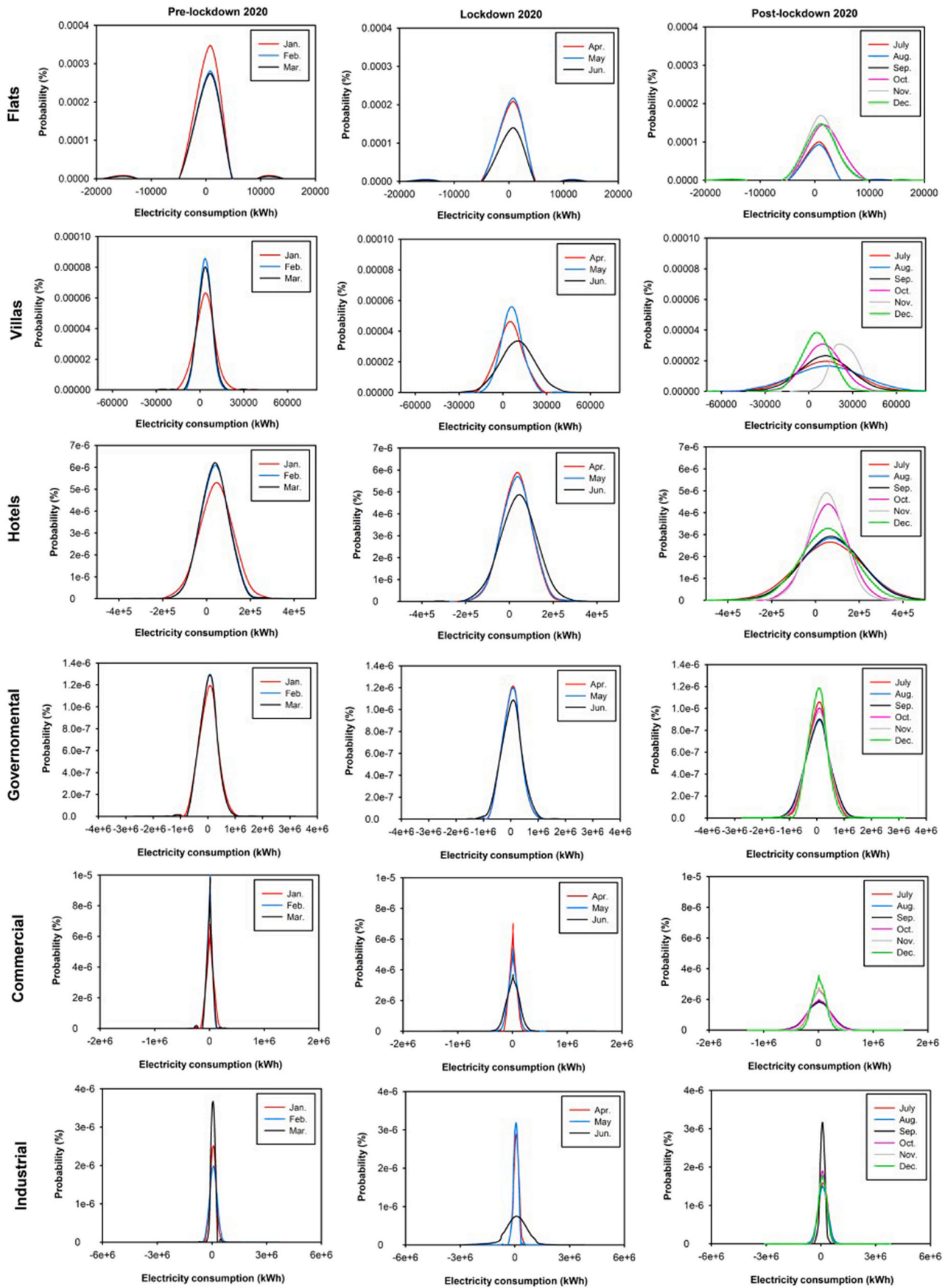Fig. 8 depicts the probability distribution functions (pdfs) of

Fig. 8. The probability distribution function of electricity consumption for the months of pre-lockdown, lockdown, and post-lockdown.

electricity consumption during all months of 2020. Results are presented for each month during three different periods: pre-lockdown, lockdown, and post-lockdown. Herein, more flattened and left-skewed curves suggest an increase in consumption and vice versa. As illustrated, it seems that the most rapid growth in electricity demand was noted in the residential sectors (i.e., flats and villas), especially during the post-lockdown period. Similarly, Fig. 8 informs that a rapid increase in hotel consumption occurred only in the post-lockdown period, especially in the July–October period. The increment in energy demand was more noticeable for the commercial sector in the post-lockdown period, especially in July and August. On the other hand, a comparison of the pdfs for all sectors indicates that COVID-19 restrictive measures less impacted the industrial and governmental sectors. For example, there were not many differences in the industrial consumption of electricity for the three sub-periods. However, there was a notable increase in this consumption in few months (e.g. May, July, and December). A similar scenario was also evident for the governmental sector.

5.2. Spatial variation of electricity consumption prior and during the pandemic

The electricity consumption was affected by different power system load profiles prior to and during the pandemic period in the study area. Hotspot and cold spot analyses were performed for three durations during the years 2019 and 2020, as shown in Fig. 9. The focus is to show spatial variations in electricity consumption patterns during the pandemic. In general, the figure shows that both hot and cold spots were reduced during 2020, apart from the post-lockdown period, while the hotspot areas increased slightly. In 2019, high electricity consumption (hotspots) is concentrated in the southern and eastern parts of the city, and to a lesser extent in some parts of the middle of the city. The southern part of the city contains a high portion of industrial and commercial areas as well as many high-density population areas where workers reside. The hotspots are clustered in industrial and commercial areas, such as Abu Hamour and Al-Maamoura. The presence of these

hotspots was consistent during the three-time states. The eastern part of the city contains mainly high-rise commercial and governmental buildings, particularly in the West Bay area. Furthermore, some hotspots are distributed in the central areas of the city like Al-Sadd and Ar-Rayyan. These areas are mainly commercial and residential areas. On the other hand, low electricity (cold spots) consumption areas are present mainly in the northern (i.e., Al-Markhiya, Umm Lekhba, Al-Kharaitiyat) and central parts of the city (i.e., Ar-Rayyan). The cold spot is present in one location in the southern part of the city. The area is known as Umm Al-Seneem which is mainly a residential area with low population density. The figure shows that the spatial distribution of the hotspots and the cold spots is consistent over time in the three states during 2019.

The spatial distribution of hot and cold spots has changed dramatically during the pandemic year 2020. In the pre-lockdown state, the hotspots were distributed in the southern and northeastern parts of the city. In the southern part, hotspots are present due to the industrial activities in that area, while the northeastern parts are clustered with more residential load, such as in the Lusail area, and the commercial and government buildings such as in the West Bay area. In the lockdown state, the areas with high electricity consumption decreased, particularly in the southern part (the industrial area), due to the temporary shutdown of many industrial and commercial activities in that area. In addition, many other areas in the northern and eastern parts of the city witnessed an unusual drop in electricity consumption, as illustrated by the spatial distribution of the hotspots. After easing or lifting the lockdown, electricity consumption increased in many areas of the city, particularly in the industrial areas in the south. On the other hand, electricity consumption increased over time in many city areas, given that the areas with cold spots declined. Most of these areas are residential areas.

The spatial changes in electricity consumption between the years 2019 and 2020 are depicted in Fig. 10. A drop in electricity consumption in the industrial areas during the lockdown state was observed. However, the increase in electricity use occurred in the residential areas in
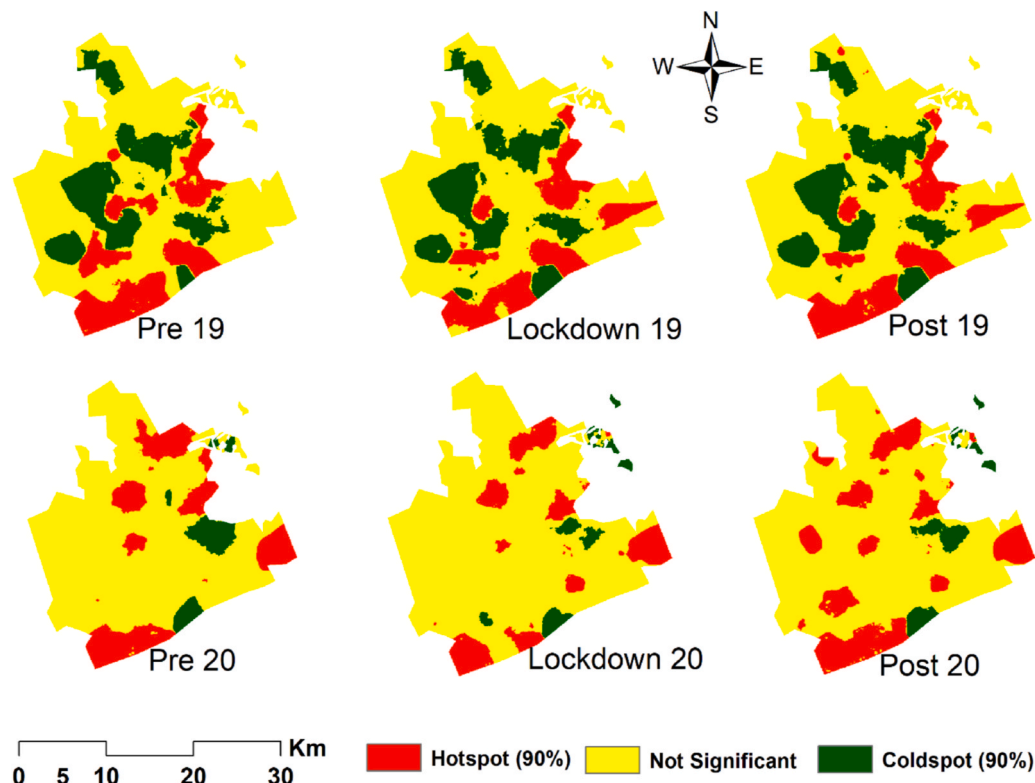
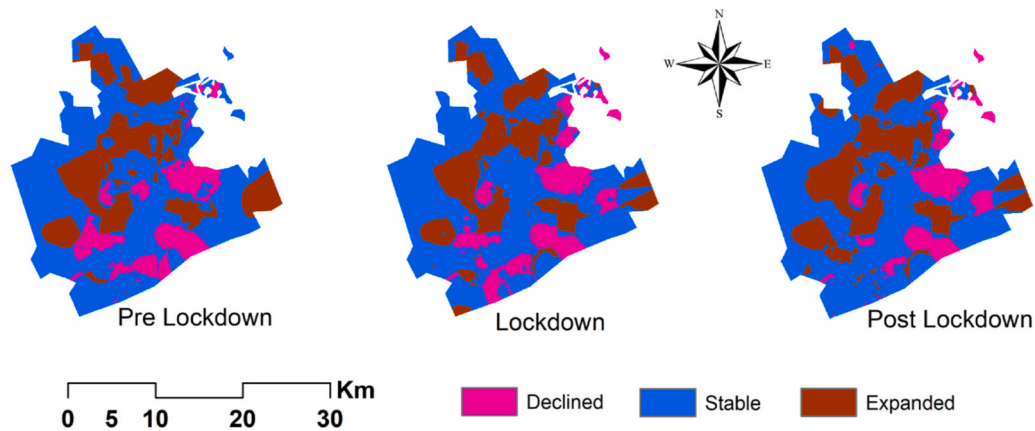**Fig. 9.** Hot-/cold-spot distributions in 2019 and 2020.

Fig. 10. Differences in the spatial distribution of hot-/cold-spot between 2019 and 2020.

the middle and northern parts of the city. The increase in electricity consumption is consistent over time. However, there is a slight change in the increase or decrease in electricity consumption during the lockdown state. Furthermore, the drop in electricity consumption areas is consistent overtime during the three phases with slight changes, particularly during the lockdown phase. In general, the hot/cold spots area has declined spatially during the pandemic year, as indicated in Table 2. As shown, the hotspot areas increased only in the post-lockdown phase.

6. Discussion and concluding remarks

During the COVID-19 era, large-scale human activity restrictions were implemented to prevent disease spread. Most Middle Eastern countries, including Qatar, implemented restrictive lockdown measures starting late March 2020. These strict preventive lockdown measures halted the activities of numerous businesses such as catering restaurants and entertainment, as well as full-time education. These restrictions reduced industrial activity and traffic, especially during the first non-working weeks of the pandemic. Numerous studies assessed the spatial patterns of COVID-19 spread in the region (e.g. Ref. [54]) and their driving forces (e.g. Refs. [55,56]), and impacts on air quality (e.g. Ref. [57]) and urban climate (e.g. Ref. [56]). Nonetheless, few attempts have been made to assess the impacts of restrictive measures during the lockdown periods of this pandemic on socioeconomic sectors like electricity consumption. As expected, the propagation of the pandemic (COVID-19 case) created unusual changes in the electricity load profile that initiated worldwide challenges to electricity planning at the generation, transmission, and distribution levels. These challenges and changes are dynamic due to the spread of the disease and the mitigation measures imposed by countries to slow down the spread of the disease. Therefore, it is paramount to analyze the spatial and temporal effects of the pandemic propagation on operating electricity plans. Furthermore, considering different socioeconomic sectors gives a comprehensive assessment of the dynamic changes in electricity demand and consumption. Therefore, this study provided an empirical analysis of electricity demand and consumption over space and time and across six socioeconomic sectors in Doha City, the capital and most populated city in the State of Qatar.

The electricity consumption decreased in the industrial and commercial sectors, particularly during the lockdown state, impacting the overall electricity consumption. The commercial sector was negatively impacted more than the industrial sector during this phase. This occurred due to closing all non-essential services and advising people to work from/stay at home. The electricity consumption in this sector decreased during all months of the lockdown phase. Likewise, the hotel sector was negatively affected by the lockdown measures. However, the increase in electricity consumption during the post-lockdown state was more linked to two main reasons. First, travelers returning to Qatar must be quarantined for one week in a hotel before leaving to their houses and completing the 14-day quarantine. This increased the occupancy of the hotels during the post-lockdown phase, which affected electricity consumption. Second, the elevated increase in electricity consumption in July and August is mainly due to air conditioning used for cooling.

The residential sector encountered different patterns during the pandemic compared to other sectors. These pattern changes are noticeable during the lockdown and post-lockdown states. During the lockdown state, the residential sector encountered increases in electricity consumption compared to the same period in previous years. This increase is mainly related to the stay-in-home measure, where authorities asked people to leave their houses only for essential services. Furthermore, many private and public companies and entities asked their employees to work from home, especially school and university students. This change in lifestyle patterns increased residential electricity consumption. In the post-lockdown phase, although the workforce fully or partially operated from their workplace, the international travel restrictions during the summer of 2020 discouraged many Qataris and expats from traveling outside the country. In addition to the high temperatures during the summer, the intensity of using air conditioning for cooling is elevated and puts more pressure on the electricity grid, which changes the load profile in many sectors (commercial, industrial, and government).

Spatially, the higher electricity consumption was noticed in the southern and eastern parts of the city. Most of the industrial services are most likely focused on the southern part of the city. It is well known that industrial activities consume a high portion of the electricity compared to other sectors. Furthermore, industrial activities attract related commercial services and residential areas for the workforce. These sectors increase electricity demand, which is present as hotspots in the southern part of Doha city. This pattern was changed during the pandemic year, particularly during the lockdown period, since industrial and

Table 2
Changes in the hot/cold spots areas (Km²) between years 2019 and 2020.

Description	Pre 19	Pre 20	Difference	Lockdown 19	Lockdown 20	Difference	Post 19	Post 20	Difference
Cold spot	101.775	27.45	−74.325	102.803	18.926	−83.877	107.384	21.756	−85.628
Not Significant at 90% level	320.685	400.143	79.458	324.348	432.428	108.08	320.555	396.718	76.163
HotSpot	99.468	94.335	−5.133	94.778	70.575	−24.203	93.99	103.456	9.466

commercial services were minimized to slow the spread of the disease. In the post-lockdown period, electricity consumption in the southern part of the city increased as the areas, as revealed by the expansion of the hotspot areas. This increase is related to the full opening of the industrial and commercial sectors and the resumption of production and non-essential services. Likewise, the electricity consumption in the post-lockdown states in the year 2020, represented by hot/cold spots, clustered in different city areas due to commercial activities or residential areas. The total area of hot/cold spots encountered dropped in the pandemic year, at the expense of normal and moderate electricity consumption in the city. This is mainly related to the restrictions on people's mobility and non-essential services during the pandemic. Empirical analysis of electricity consumption in Doha city reveals heterogeneity patterns in the study area over space and time is presented in this study. This heterogeneity is related to the characteristics of land use in the city and the distribution and concentration of the different socioeconomic sectors within the city boundaries.

To conclude, this study assessed the impact of the COVID-19 pandemic on the spatial and temporal characteristics of electricity demand and consumption across different socioeconomic sectors in Doha (Qatar). A geospatial analysis was conducted for three different temporal periods in 2020, which summarize different restriction measures. These periods are pre-lockdown, lockdown, and post-lockdown. The electricity consumption in these periods were compared to those over the same time frame between 2017 and 2019 to investigate the impact of the pandemic on electricity consumption. Assessing spatiotemporal electricity consumption is based on real data using spatial and statistical tools. The results show a drastic change over time and space and across sectors. Most notably, we observed an increase in electricity consumption in the residential sector, while there was a decline in other sectors during the lockdown period. Spatially, the spatial distribution of the hot and cold spots changed dramatically during the pandemic year of 2020. The spatial changes in electricity consumption were more notable in the southern part of the city, which is characterized by high population density and the concentration of light industrial and commercial activities.

Mapping and visualizing hotspots and cold spots of electricity consumption enables policymakers to determine how and where the electricity consumption varies over time under risk. Consequently, building spatial hotspots and cold spots maps can be an essential spatial guideline tool for policymakers to manage electricity demand and consumption at the time of risk and to identify the elements that lead to high or low electricity consumption in certain areas. Quantifying spatiotemporal changes in electricity consumption can provide explicit information about the demand for this resource, and can scale up intervention pathways to identify the local and sector demand dynamics due to imposing different mitigation and restriction measures to reduce the risk of the spread of the disease.

Credit author statement

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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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