The Effects of Social Distancing on the Temperature-Demand Relationship

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ABSTRACT

To mitigate the spread of the Novel Coronavirus (COVID-19), governments around the world have imposed social distancing policies ranging from minor social activity suspensions to full curfews. These social distancing policies have altered electricity consumption behaviors in numerous countries. This paper studies how strict social distancing policies affect the relationship between electricity demand and ambient temperature. This relationship is especially important since most governments imposed strict social distancing policies during a temperature transition season where the impacts of temperature variations are particularly important for grid operations. In this paper, we first review the expected short- and long-term impacts of social distancing on the electricity demand. We then present a case study on the electricity demand of the Kingdom of Saudi Arabia during strict social distancing policies. The results of this case study suggest that strict social distancing policies result in a stronger dependency between temperature and electricity demand. Additionally, we observe a reduction in the time required for the electricity demand to respond to temperature changes. Power system regulators can use the results in this paper to better design energy policies and cope with rare events. Additionally, power system operators can use the results in this paper to more accurately forecast electricity demands to avoid inefficient and insecure operation of the electric grid.

1. Introduction

Global-scale disruptions, such as the Novel Coronavirus (COVID-19), are rare. This virus has impacted every aspect of our lives and changed the manner in which we interact with our environment. As of October 2020, the pandemic has resulted in more than one million deaths and 36 million infected persons [1]. Governments around the world have imposed social distancing policies, such as requiring a minimum of a six-foot separation between people and curfews of public places [2]. By minimizing person-to-person contacts, these policies reduce the spread of the virus [3, 4]. Social distancing from COVID-19 has a profound impact on the global economy, energy trade, and individual psychology, and consumption behavior (e.g., see [5–10]).

The pandemic has altered the daily routines of individuals in many aspects. Social distancing has significantly modified people's consumption behaviors [5, 6]. For instance, with people staying home more frequently, on-line shopping and food delivery services have grown significantly. On the other hand, many commercial activities have completely or partially shut down during the strict social distancing measures [11]. Social distancing has disrupted the social system in various ways, which, in turn, have significantly changed global consumption behaviors. Numerous examples of large-scale consumption behaviors have emerged during COVID-19, such as avoiding public transportation [6], an increasing consumption of plastic materials [12], and an unprecedented demand on healthcare facilities, influenced by the implementation of new healthcare procedures. Many other socioeconomic factors have also contributed to changes in demand, such as travel bans, unemployment, and government interventions to stimulate economies [2, 13].

1.1. Electricity Demand and COVID-19

Restrictions on social activities and policies imposed to mitigate the spread of the pandemic have significantly impacted the electricity demand. Many countries have reduced their consumption of nearly all energy resources [14]. The electricity demand decreased by around 20% in several countries around the world [15]. The closing of large social gathering places has reduced electricity demands from the government and commercial sectors. The industrial sector also faces several changes, as numerous manufacturers have closed or are reducing their demand, whereas other manufacturers are actually increasing their demands [16, 17]. These changes in the demand can be observed as a shift from one sector to another. However, this alone does not provide information on the electricity demand, as the consumption behavior depends on consumer location and the efficiency of the end-use load, as well as other socioeconomic factors [18, 19]. Lower electricity demand results in reductions to overall operation costs and CO_2 emissions. However, one needs to be careful before making inferences about socioeconomic changes without considering the other external factors, such as the social structure changes and temperature variations, and their interdependencies with the electricity demand.

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1.2. Social Impact and COVID-19 Electricity Demand

The dependency between electricity demand and social activity is evident. Several studies have considered the social factors that affect the electricity demand in the context of the demand forecast and/or demand response [20, 21]. The demand behavior during COVID-19, however, is different and has posed many changes [11, 22]. As mobility is restricted and consumption is concentrated in the residential sector, the daily demand patterns become more similar. This can be observed with respect to the similarities between the weekend and weekdays during curfews [10, 23]. Bahmanyar et al. [24] showed that, for countries with strict restrictions, such as Spain, Italy, Belgium, and the U.K., the demand reduction is higher than countries with less rigorous restrictions, such as Sweden. Furthermore, Narajewski et al. [25] investigated the electricity demands of five European countries and suggested that the pandemic impact on the consumption behavior might be permanent.

A quantitative analysis in [26] shows the impacts of social distancing policies on electricity demand, power system security, generation mix, and retail electricity price in the United States. The analysis highlighted several abnormalities in the electricity demand with diverse responses to the social distancing polices observed in different operation areas [26]. Other results in [19] show a strong correlation between the electricity demand reduction and the number of COVID-19 cases, the strictness of social distancing restrictions, and the level of commercial activity. These authors emphasize the importance of considering locational socioeconomic variations and the need to augment cross-domain data to understand the electricity demand [19]. For instance, the impact of social distancing policies on the electricity demand in India differs between regions based on their consumers' wealth. Compared to low-income regions, the electricity demands in affluent regions of India more quickly returned to similar levels as before the pandemic once the government relaxed the social distancing restrictions [27].

1.3. Cooling Demand in Hot Countries

The electricity demand during COVID-19 has previously been used to infer information on socioeconomic and environmental changes. Numerous studies have used the electricity demand as a tool to analyze the changes occurring in other systems (e.g., socioeconomic [28, 29] and greenhouse emissions [14, 30]). However, the suspension of most social activities occurred from March to April 2020 [15]. Such periods are characterized by significant temperature fluctuations, which complicates the process of extracting social insights based on the electricity demand data. For instance, Narajewski et al. hint in [25] that the high-temperature dependency of the electricity demand in France have intensified the impact of COVID-19 on the electricity demand even before imposing strict social distancing policies.

Considering the impacts of temperature is crucial for understanding electricity consumption behaviors. This is especially the case for countries with high proportions of cooling and heating loads. In extremely hot weather, the cooling demand can reach up to 71% of the total residential electricity demand (see, e.g., [31]). Furthermore, previous studies have shown that more than 75% of the electricity demands of high-rise buildings are used for heating/cooling and ventilation purposes [32]. Another study has shown that an increase in the demand varies from 0.5% to 8.5% per degree Celsius increase in the temperature [33]. Currently, the cooling demand is estimated to consume 20% of the global electricity demand. Further, cooling demands are rapidly increasing, as evidenced by the fact that cooling was the fastest growing energy end-use in building electricity consumption between 1990 and 2016 [34].

The cooling demand is expected to continue to grow given the rise in temperatures due to climate change [35]. Innovations in the power sector and the decreasing cost of energy are expected to lead to an expansion in the number of air conditioning units from 1.6 billion in 2018 to 5.6 billion by 2050 [34]. A study shows that 38 out of 50 most populated metropolitan areas around the world are in developing countries, and most of them face warm to hot weather conditions; hence, an unprecedented increase in the global cooling demand is expected as incomes increase in developing countries [36]. For these reasons, there have been extensive studies of the cooling loads in many countries such as the United States [37], India [38], Spain [39], Brazil [40], China [41], and Saudi Arabia [42–46].

In this paper, we use Saudi Arabia as a case study for investigating the impacts of social distancing policies on total electricity demand while considering temperature variations. The Saudi electricity demand is highly dependent on the temperature. This temperature dependency is particularly pronounced in the residential sector, which accounts for a large portion of both the total demand (45.6%; see [47]) and the overall cooling demand (more than 50% in normal years). The significant variation in the temperature during the period of this study, from 17°C to 40°C, allows us to explore the relationships among the electricity demand, ambient temperature, and imposed social distancing policies.

1.4. Contributions

The COVID-19 pandemic has created an unprecedented opportunity for a natural experiment to examine electricity demand. The unique characteristics of the electricity demand during the imposed social distancing policies due to COVID-19 and the seasonal transition (i.e., from winter to summer for the northern hemisphere) have intensified the impact of the cooling demand in the residential sector, allowing a more profound investigation of the interdependence among energy consumption behavior, temperature, and the social system. As such, our main contributions can be summarized as follows:

- We describe the anticipated short- and long-term impacts of social distancing on power systems. We also review the short-term impacts on the electricity demand that have been reported from different countries.

- We present a detailed case study analyzing the electricity demands and ambient temperatures before, during, and after imposing various social distancing policies. We discuss the effect that social distancing has on the demand–temperature relationship, and we show, through this case study, that the evident shift towards the residential sector has caused unprecedented levels of correlation between the demand and temperature.

Factors impacting the correlation between the temperature and electricity demand during strict social distancing policies in the presented case study belong to two general categories: (a) the hot weather conditions, as the polices were imposed during a transition season with a significant increase in the temperature, and (b) the increased proportion of residential load, which is highly dependent on temperature. Although there is a substantial existing literature studying the effects of temperature on electricity demands in many countries, the consideration of temperature–demand correlation and the associated changes during strict social distancing have not yet been addressed. With this work, we study how the temperature–demand correlation has changed via deducing information from the electricity demand during COVID-19, especially in countries where the two aforementioned factors apply.

Roadmap. The rest of the paper is organized as follows. Section 2 discusses the social and temperature impacts on the electricity demand. Section 3 describes the short- and long-term impacts that social distancing has on power systems. Section 4 introduces our case study and shows how the electricity demand is affected by social distancing policies. Section 5 presents the results and main findings of our study. Section 6 concludes the paper.

2. Factors Influencing Electricity Demand

The power system is the largest physically interconnected human-made system, supplying modern societies with the energy needed to support social and economic development. Power system operators aim to efficiently and reliably produce energy from generators to supply all electricity demands. Power system reliability is especially crucial for critical demands such as healthcare facilities, city centers, industrial facilities, emergency shelters, and other loads that are essential to operate the basic needs of modern societies. To maintain an acceptable level of reliability to critical and non-critical demands, the external factors impacting the electricity demand need to be carefully studied and included in the electricity forecasting models. This is particularly important during rare events, such as a pandemic, as the energy consumption behavior is unknown and never encountered before. We discuss the importance of understanding the electricity demand in Section 2.1, and then focus on two main external factors, namely, variations in ambient temperature in Section 2.2 and large-scale social changes in Section 2.3.

2.1. Electricity Demand Forecast Accuracy

Acquiring highly accurate information about electricity demand plays a major role in the day-to-day operation of power systems. Generally speaking, over-forecasting the demand could lead to underutilizing the committed generating units and, hence, less efficient operation, while under-forecasting the demand might compromise the power system reliability. Many factors influence the electricity demand with varying degrees, such as the time of day, daily life activities, economic factors, weather forecast, and random or occasional social events [48]. Some of these factors are uncontrollable, difficult to predict, location-specific and their direct influence on the load demand is hard to measure. Understanding the demand with high spatial and temporal resolution considering the location-specific features is important to enhance the demand forecast.

Understanding the demand is also crucial for long-term planning of power systems. Planners attempt to determine the most efficient approach for supplying future electricity demands. Transmission expansion planning is a variant of the planning problem in which the physical power system network is considered to ensure adequate transmission capability [49]. Typically, a long-term demand forecast, ranging from 10 to 30 years, is used as input for long-term planning tools. Planners perform detailed analyses to understand the factors that influence the demand at each location within a power system. This process is periodically revisited to correct the plan and cope with unexpected changes in order to ensure meeting the demand in the most cost-effective way.

2.2. Temperature Impact on Electricity Demand

The electricity demand is highly influenced by the ambient temperature, especially in countries characterized by extremely hot or cold temperatures. The correlation between electricity demand and ambient temperature in such countries is significant [44]. Temperature data is widely used in daily power system operation and planning. The relationship between the demand and temperature depends on many socioeconomic and technical factors, such as electricity tariffs, cooling device standards, insulation requirements, and population awareness regarding efficient energy end-use; hence, the temperature's influence on the electricity demand is impacted by social changes.

Extreme temperatures have a variety of impacts on the efficiency of a power system. For example, the efficiency of the cooling loads strongly depends on the environment and the ambient temperature surrounding the cooling load, which is impacted by the urban heat island (UHI) effect. The UHI effect increases the heat in an urban area due to large-scale modifications of the land surface and human activities that impact the flow and storage of heat, water, and air [50, 51]. As the temperature increases, the air temperature in an urban area becomes higher than the air temperature in outlying areas, which leads to an increase in the cooling demand and a decrease in the overall efficiency. The temperature also affects the efficiency of power system transmission; a higher temperature implies the incursion of more losses by the transmission system due to ohmic losses. The relationship between electricity demand and temperature becomes more complex when considering the locations of the loads and their environments.

2.3. Social Influence on Electricity Demand

Changes in the social system highly influence the electricity demand. Demand forecasting models employed by power system operators usually consider nation-wide social events (e.g., holidays) and sudden social changes (e.g., school openings, daylight saving time changes, major sport events) [52]. Forecasting models use historical demand data to infer consumption behavior and improve the forecast accuracy. However, during rare events similar to the pandemic, the demand is unusual and historical data does not capture the consumption behavior. We emphasize that previously known interdependence between the electricity demand and other external factors such as temperature might not be accurate anymore and there is a need to recalibrate the forecasting models to account for the unusual consumption behavior.

3. The Impact of Social Distancing on the Power System

Social distancing policies imposed due to COVID-19 have significantly disrupted power systems. The impacts of social distancing policies may vary from very short-term, as a response to the imposed policies, to long-term factors that might permanently change the electricity consumption behavior. This section discusses both the short- and long-term impacts of social distancing policies on power systems.

3.1. Short-Term Impacts

The impact of COVID-19 on the electricity demand around the globe depends on social distancing restrictions. During full curfew, France, India, Italy, Spain, and the U.K. experienced a minimum 15% decrease in their daily electricity demand relative to 2019 [53]. Furthermore, throughout March and April 2020, the central region of the United States experienced a 9%–13% reduction in weekday demand, as compared with the expected demand [54]. In addition, an 8.2% decrease in the daily power generation occurred in China throughout January and February 2020, as compared with 2019 [55]. Although the residential demand should be characterized by a significant increase, the total reductions in the demand can be attributed to a significant decrease in the demand from large-scale industrial and commercial sectors. In China, the demand of the industrial sector (68% of the total demand) reported a decline of 12% [15].

The New York Independent System Operator reported a reduction in the New York City electricity demand by 6% to 18%, while the electricity demand of an average apartment increased by 7% to 23% during working hours, with a slight decrease in the demand during non-work hours [56]. The changes in demand experienced by most utility companies in the United States varied from one location to another. Substations that primarily served residential loads faced high demand while many other substations had noticeable reductions in demand. This observation is a result of mobility restrictions and the manner in which the electricity demand is concentrated in the residential sector. Further, the seasonal temperature rise noticeably increased the residential demand in many countries around the world during the imposed social distancing polices [10]. In summary, the electricity demand is impacted by two factors (i.e., the strict social distancing policies and the increase in the ambient temperature) that significantly increased the residential demand in many countries around the world [10].

The short-term impacts of COVID-19 on the power system are not limited to changes in the demand. Ensuring personal safety while maintaining continual operation presents a significant challenge to power system operation [57]. Different practices and procedures have been implemented by utility companies to cope with the pandemic impacts. For example, utilities had postponed many unnecessary maintenance activities during the pandemic and implemented strict precautionary measures when performing repair and maintenance operations [58]. While not the focus of this paper, COVID-19 has had many other short-term impacts for utility companies. Refer to [57–60] for more details about utility companies' experiences and responses during the strict social distance policy period.

3.2. Long-Term Impacts

The end of the pandemic remains uncertain. The strictness of social distancing policies, and thus the impact on electricity demand, varies with the severity of the pandemic in each region. This uncertainty imposes substantial challenges to the systems impacted by the spread of the pandemic and may lead to changes that will endure even after the synthesis of a reliable vaccine [61]. In the long-term, the price of electricity and advances in technology have a dominate influence on the electricity consumption [62]. However, the changes in consumer behavior due to social distancing may persist for longer periods and may not return to their previous state. The characteristics of electricity demand after removing the social distancing policies are hard to predict. However, several examples of large-scale changes in consumption behavior due to restricted social distancing measures suggest that the electricity demand will also experience changes. Furthermore, the return-to-normal may cause the energy consumption to rebound in a manner that will eliminate all of the benefits and emissions reduction that occurred during strict social distancing, possibly becoming higher than the level of consumption before COVID-19.

The priorities of governments and investors around the world are changing to adapt to this uncertain period [59]. These uncertainties will impact future plans and power system development. The International Energy Agency predicts that the renewable resources installed during 2020 in the United States will be 13% lower than that in 2019 [15]. Utility companies have delayed a number of projects that had been planned for completion within the next five years. Accordingly, system operators will need to rely on existing generators to meet the short-term demand. However, in the long-term, the price of renewable energy should continue to decline, such that renewable energy may provide many desired advantages [63]. Renewable energy projects can stimulate the economy and aid in the job creation process after the pandemic [53, 63].

There are numerous signs that the change in the demand due to social distancing may continue even after the elimination of strict social distancing measures [64]. Social distancing forces people to stay at home more, which increases the residential demand. Social distancing measures have forced many companies and government entities to practice "Work from Home" (WFH) policies at a scale that has never occurred before. WFH causes employees to uses their own internet connection and air-conditioning, as well as to pay for their energy consumption during working hours. Many organization observed multiple advantages from these WFH policies and will likely attempt to integrate these policies as part of the future manner of conducting business [23]. Furthermore, the education system is experiencing a significant increase in the amount of online learning. Universities and schools around the world found themselves forced to move to online education during social distancing. This movement injected billions of dollars of investment and increased the amount of innovation in online education [65], such that it is expected to be extensively used in the future. Telemedicine is another emergent concept resulting from social distancing. During a telemedicine appointment, the basic medical material and pre-examination equipment are procured by the patient. Although the electricity demand may not be significant, the example of the telemedicine provides insight into how energy consumption may shift to the residential sector in the future as more services are performed from home.

4. Case Study: Impact of Social Distancing on the Electricity Demand of Saudi Arabia

This section analyses the electricity demand of the Kingdom of Saudi Arabia (KSA) and the impacts caused by the imposed social distancing policies. We begin by presenting an overview of the Saudi power system in Section 4.1. Next, in Section 4.2, we describe the social distancing policies imposed in the KSA to fight the virus. Then, in Section 4.3, we illustrate the electricity demand trends observed during the social distancing measures. Finally, in Section 4.4, we present the core analysis of this section by incorporating temperature data into the analysis.

4.1. State of the Power System in Saudi Arabia

The power system in the KSA is operated by the Saudi Electricity Company (SEC), which also own most of the power system infrastructure. Over 30 million people are served by the Saudi power grid, with a peak demand of 62 GW and an energy consumption of 289 TWh in 2019 [47]. The load factor, defined as the average demand divided by the peak demand over some period of time, indicates how fully the generation units are utilized. In the KSA, the load factor is as low as 0.53. This low load factor is attributable to the high summer temperature and resulting cooling requirements causing a strong seasonal variation in the electricity demand of the KSA.

The total installed capacity of the generation in the Kingdom is 88.7 GW, where 66% of the generation is owned by the SEC and the remaining 34% by different independent power producers. The generation mix in the KSA is mainly based on fossil fuels, where natural gas accounts for 37% while the remaining 63% is served by oil products. Renewable energy represents only a small fraction of the generation mix. In 2017, however, the government announced the National Renewable Energy Program (NREP) as part of its Vision 2030 initiative to install 9.5 GW of renewable energy resources by 2023 [66].

In 2019, the demand in the Kingdom was distributed among the electricity sectors as follows: (a) residential (45.6%), (b) industrial (17.6%), (c) commercial (16.7%), (d) governmental (13.5%), and others (6.2%) [47]. The building demand, which contains the residential and a small amount of other sectors, represents 70% of the demand in the KSA. A building stock model developed in [45] shows that 66% of the total energy end-use for the buildings in the KSA is space cooling demand. The extreme heat during the summer leads to this excessive cooling demand. We note that the power losses in the transmission and distribution network account for 9.26% of the generated power [47].

Motivated by the awareness of finite oil resources and increasingly inefficient consumption behavior, several energy efficiency polices have been established by the government to promote energy efficiency measures [42]. These policies have two main goals: (a) increase the efficiency of cooling appliances and (b) enhance building insulation. Recent policies enforced in the KSA prohibit connecting electricity services to residential customers that do not meet the insulation requirements. A previous study has shown that fully implementing these efficiency polices could lead to annual reductions of 33.6 TWh and 24.0 million tons of carbon emissions [67]. Nonetheless, another study shows that 70% of the residential load has insulation that is not compliant with the new standards [68], which creates a substantial challenge with respect to achieving these efficiency goals.

4.2. Social Distancing Policies

Since the first case of COVID-19 was detected in the KSA on March 2, 2020, the KSA implemented a series of actions to prevent the spread of the virus, as summarized in Figure 1. Since June 21, the Saudi government lifted the curfew on most of the regions in the country. However, less strict social distancing measures are still enforced, e.g., many large social gathering activities remain restricted.

4.3. Demand Trends during Social Distancing

Figure 2 shows the hourly demand used in this study from the beginning of 2020 until June 21, 2020. The electricity demand and temperature data are described in Appendix A. Figure 2 categorizes the policies in the previous

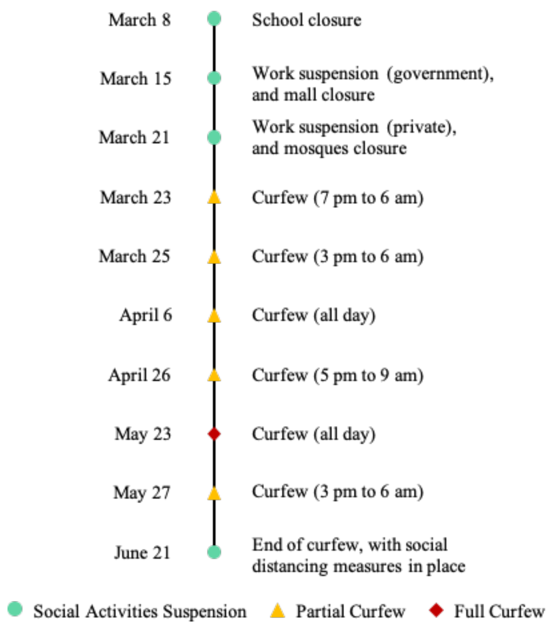

Figure 1: Social distancing policies imposed by the KSA.

subsection as either (a) social activity suspensions, (b) partial curfew, or (c) full curfew.

A decreasing trend in the electricity demand occurs during the full curfew periods. Furthermore, a general increase in the demand can be observed as summer approaches at the end of April. As the imposed social distancing policies became stricter (i.e., from the green period to the red period), weekday demand profiles became more similar to weekend profiles. In addition, we observe that the magnitude of the oscillation in the daily demand during the middle of the full curfew period was less than the other periods. The average daily variation between the peak and valley during April 2020 is estimated to be 4.92 GW (i.e., 8.1% of the 2019 peak demand), as compared with variations of 6.00–6.79 GW (i.e., 9.8 to 11.1% of the 2019 peak demand) observed since April 2016. Such findings suggest that the demand concentration in the residential sector leads to a more similar consumption behavior due to the reduced consumption distribution over the day, i.e., similar energy end-use and appliance efficiency over the day. Table 1 depicts the relationship between the peak demand and temperature in April. Comparing 2020 with 2019, the peak demand and energy consumption in April increased by 3.53% and by 3.15%, respectively.

4.4. Relationship between Demand and Temperature

Figure 3 shows the daily peak demand and average temperature of the KSA from the beginning of 2020 until June 21, 2020, as well as a zoomed-in view of the full curfew period from April 6 to 26, 2020. We observe that the demand generally follows the temperature. In addition, an increase, followed by a sudden decrease, in the temperature coincides with the full curfew periods. Therefore, specifying the exact

Table 1
Demand and temperature of month of April in the KSA from 2016–2020.

Year	2016	2017	2018	2019	2020
Peak Demand (GW)	45.70	44.14	45.09	46.88	45.76
Total Energy (TWh)	23.59	22.87	23.58	24.84	22.24
Max. Temp.(°C)	40.0	38.0	38.0	38.0	39.4
Ave. Temp. (°C)	27.9	24.9	26.2	28.3	26.0
Min. Temp. (°C)	17.5	13.0	17.0	16.1	8.8
Max. Daily Temp. Variation (°C)	22.5	25.0	21.0	23.3	23.2

reduction in electricity demand that can be attributed to the curfew is difficult. Nonetheless, we observe an increase in the correlation between the electricity demand and temperature during the full curfew periods. Figure 3 also shows how closely the demand correlates with the temperature during the first full curfew. We used the *linear correlation coefficient* to measure the linear dependency, as described in Appendix B. Relative to the last four years (2016–2019), April and May 2020 had record-high levels of linear correlation coefficients between the electricity demand and temperature for the study period. Figure 6 shows the variability in the linear correlation value over the last five years. During the winter months (January and February), the demand correlation with the temperature is low in the KSA, as the demand dependence on the temperature is low in the winter.

Considering the full curfew enforced in April, we observe an interesting reduced-lag behavior between the electricity demand and temperature. Normally, the correlation between the hourly electricity demand and ambient temperature of the same hour is high; however, the correlation with the temperature of the previous hours is higher. This can be observed in the electricity demand profile shown in Figure 4 (April 2019). We observe that the demand lags behind the temperature with respect to time. This is generally attributed to the response of a cooling system to the changing temperature. As the ambient temperature increases, the thermal energy begins to penetrate the walls of the buildings. However, a building's inner temperature only substantially increases when enough energy has transferred through the walls. This process requires time and is dependent on the installed thermal insulation, causing the "lagged" increase in the demand with the response of the cooling systems. During the full curfew periods, however, we observe a reduction in the lag between the demand and temperature. Figure 5 shows the electricity demand for three days during the first full curfew (April 2020). We observe a more significant reduction in the demand–temperature lag, as compared with Figure 4 (April 2019).

A more general view of the lag reduction relative to previous years can be observed in Figure 7. The y-axis in Figure 7 shows the linear correlation between the demand at hour *hd* and the temperature at hour *ht*. The x-axis indicates the number of hours that the demand lags behind the temperature (*lag* = *hd* - *ht*). The correlation in April 2020 peaks at a 3-hour lag while the peak correlation for the last four years

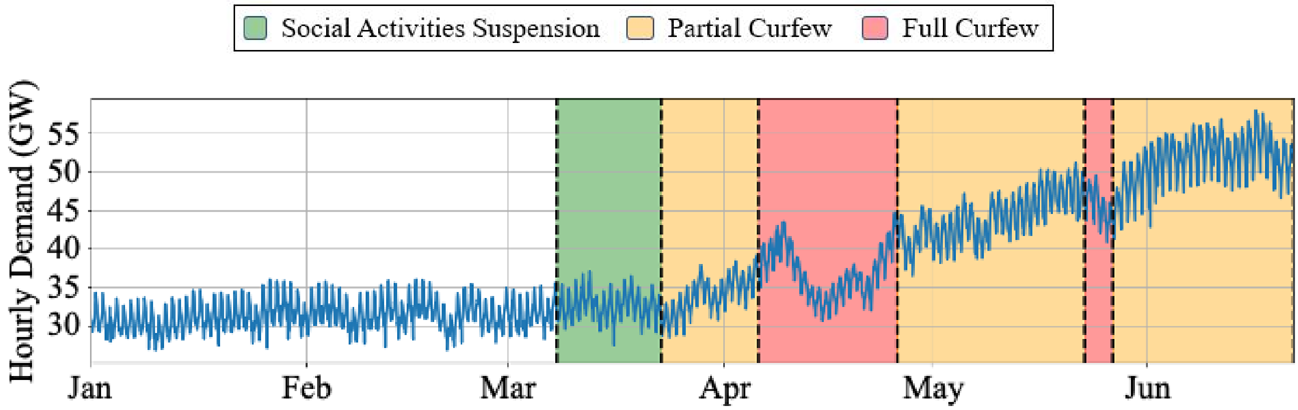

Figure 2: Hourly demand from January 1, 2020, to June 21, 2020, during different levels of social distancing measures.

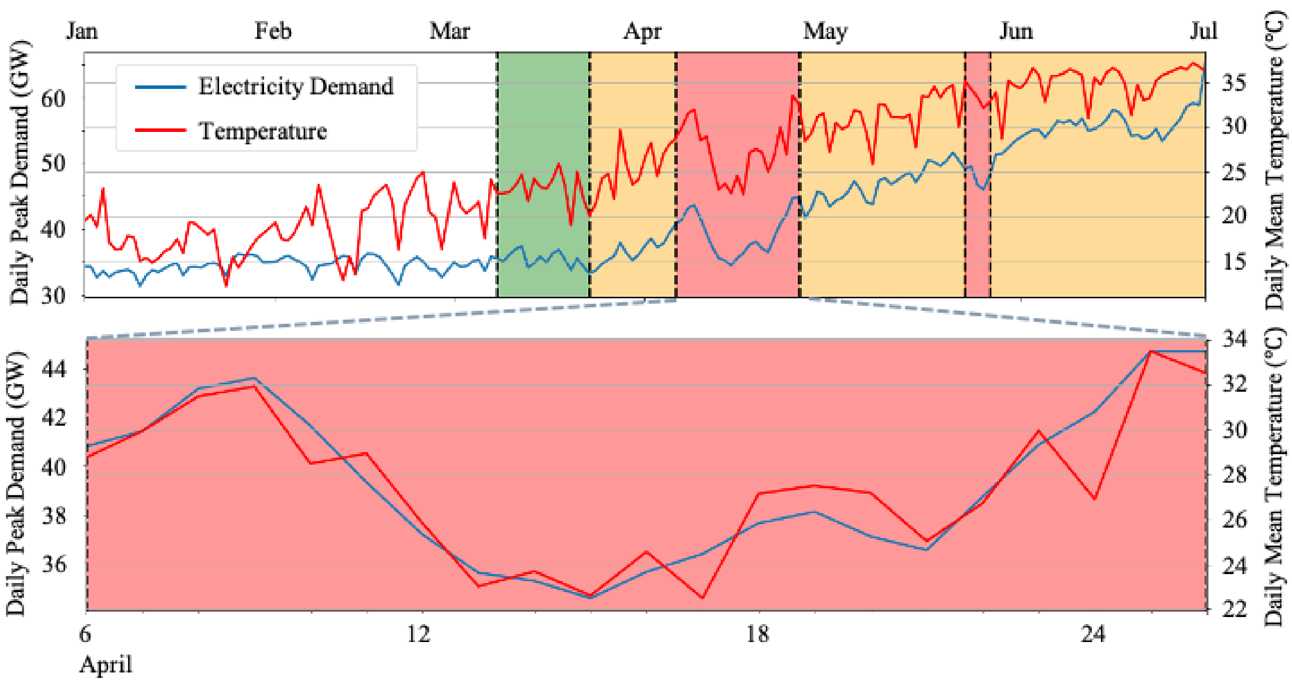

Figure 3: Daily electricity demand and ambient temperature from January 1, 2020, to July 1, 2020, before and during the imposed social distancing policies, and a zoom-in from April 6 to 26, 2020, during full curfew.

was between 4 and 5 hours. The hour when the peak correlation occurs can be used as a measure to obtain the response time of the demand to a change in the temperature. In April 2020, faster responses were observed for the demand to the changes in temperature. This may be attributed to a shift toward residential cooling and the associated inefficient insulation in residential buildings. Inefficient insulation yields a more rapid response in the cooling demand to changes in the temperature.

5. Further Discussion

5.1. Temperature, Cooling, and Other Countries

In countries like the KSA, where temperatures are extremely high, the annual peak demand typically coincides with extremely hot weather from June to August (in the Northern Hemisphere) [69]. The cooling demand is specifically important due to the impact that climate change has on the ambient temperature. The temperature is expected to rise in the near future [50], such that the dependency on cooling loads will become more relevant. Furthermore, the consumption behavior of the cooling demand plays a major role in determining the annual generation scheduling plan. In this paper we demonstrated how an event such as the pandemic can change the relationship between the electricity demand and temperature. We want to empathize here that it has become crucial to understand the socioeconomic changes that affect the demand to design improved future energy policies.

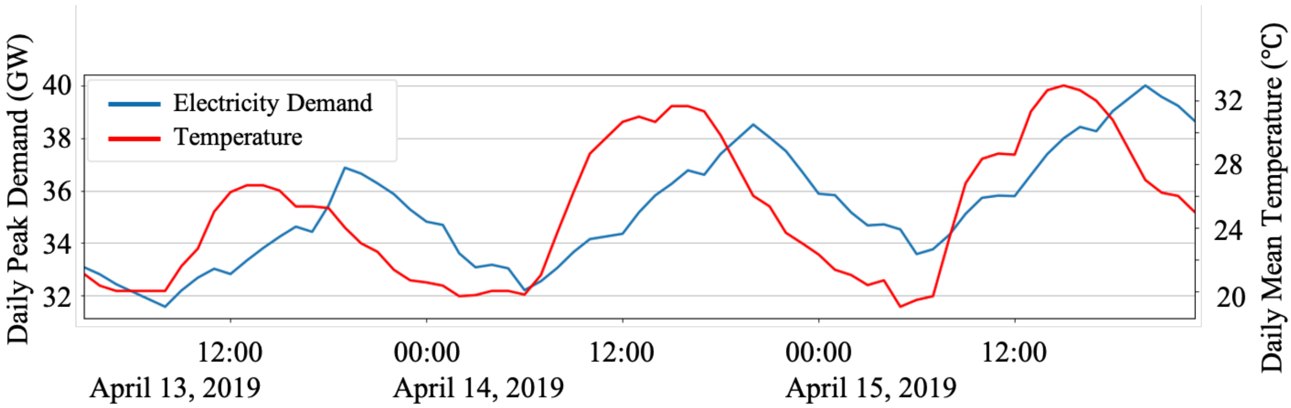

Figure 4: Electricity demands and temperatures from April 13 to 15, 2019.

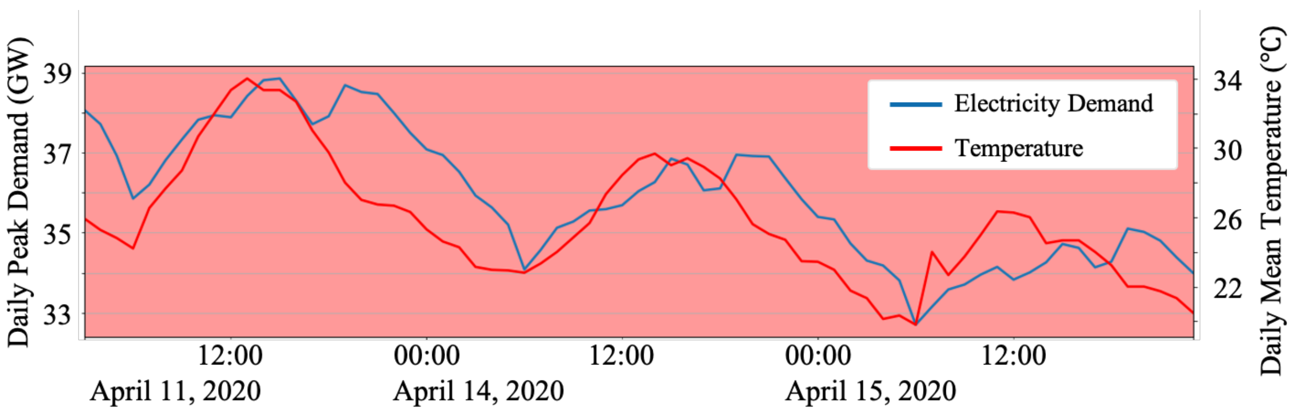

Figure 5: Electricity demands and temperatures from April 12 to 14, 2020, during full curfew.

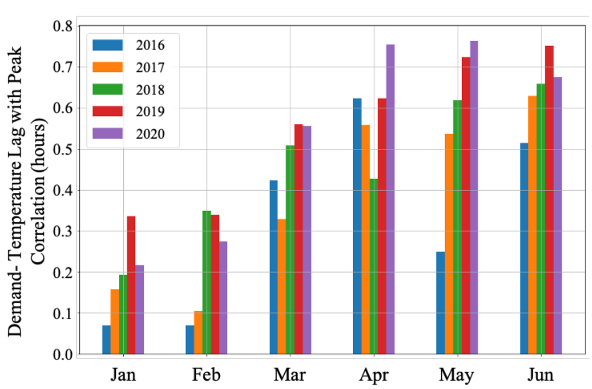

Figure 6: The correlation between the electricity demand and temperature from 2016 to 2020.

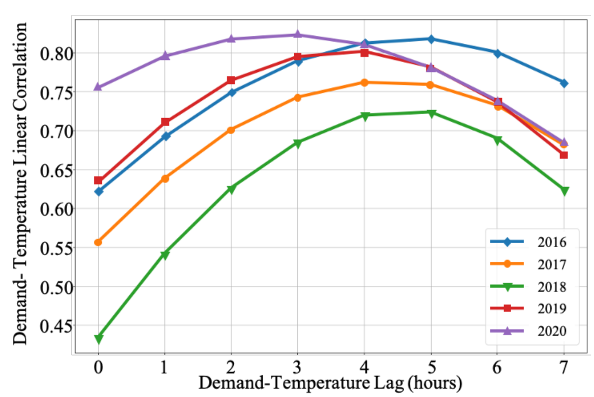

Figure 7: The correlation between the electricity demand and temperature lags in the month of April from 2016 to 2020.

5.2. Consumption Behavior Change

During COVID-19, the electricity demand clearly shifted to residential sectors, which increased the household energy consumption. The increase in the energy consumption by itself will change consumption behavior. Chen et al. [10] conducted a survey of 632 participants the from New York metropolitan area. The survey asked participants their estimated change in electricity usage during the pandemic, as compared with the months preceding the pandemic. The estimated changes were later correlated with participant willingness to pay for home energy management systems (HEMS), which is a technology that manages household consumption and minimizes household bill [70]. Those who estimated a decrease (10.4%) or increase (48.3%) in their electricity usage were more willing to pay for an HEMS than those who estimated no change (41.3%). Therefore, new energy management technologies (e.g., HEMS) may be adopted as people experience an increase in their residential demand. The adoption of HEMS will require a careful analysis to better understand the impacts of this technology on electricity demand.

5.3. Flexibility During Rare Events

The occurrence of rare events such as the pandemic results in unexpected scenarios. For the curfews, there was an increase in residential demand, with a consequent increase in consumers' electric bills. Before the pandemic, the cooling needs for an individual during the week were supplied by workplace facilities. Therefore, due to the pandemic, there was a shift in these cooling needs that required satisfaction via mostly residential air conditioning units. In addition, the high temperatures during strict social distancing measures increased the electricity demand of the residential sector. Furthermore, the increase in consumer bills in the residential sector motivates the development of flexible demand response programs and special tariff designs tailored to such rare events. From the consumers' prospective, these demand response programs may decrease the incurred cost of electricity. From the utilities' prospective, demand response programs increase the flexibility of the demand and assist in flattening the demand curve, hence increasing the economic efficiency of the committed generators. Therefore, the flexibility offered by demand response may benefit both parties (consumers and utilities) to cope with rare events.

6. Concluding Remarks and Future Work

Social distancing policies imposed to mitigate the spread of COVID-19 have disturbed normal electricity consumption behavior. Due to inhibited mobility, there has been an increase in the in-home hours of consumers. Resulting changes in the contributions of different sectors are highlighted by an increase in the residential contribution to the electricity demand. In our case study, we observed that the correlation between the temperature and demand increased dramatically during full curfew period in Saudi Arabia. Furthermore, we showed that the dynamic impact of temperature has changed due to social distancing measures. This can be attributed to the increased percentage of cooling loads due to an increase in the temperature and change in the efficiency of the loads in different sectors. Hence, social distancing measures have clearly changed the relationship between the electricity demand and temperature. This is especially salient in regions with high cooling/heating usage.

The demand–temperature lag data show the impact of social distancing measures. While we quantified the changes in the time lag during the full curfew, further analysis is required to understand how changing energy end-use efficiency affects the residential demand. Our future studies will build on this finding to further understand the demand–temperature relationship during large social changes. Furthermore, COVID-19 data provide an important opportunity to validate different building models, as people are heavily concentrated at home. Historical demand data during the imposed policies and curfews provide the opportunity to better understand the electricity demand. Mobility restrictions during the curfews shifted the demand consumption from different sectors to the residential sector, establishing a potentially semi-isolated environment for a natural examination of the loads. Furthermore, the occurrence of the imposed policies coincides with a seasonal transition period. The large temperature variations during the transition season allow us to better understand the relationship between the electricity demand and temperature.

The uncertainty surrounding the pandemic remains a major concern. Restrictions and regulations are continuously being reviewed with the evolution of the pandemic. Even after lifting the social distancing policies, people may still remain hesitant about going to their workplaces and many organizations may continue using the WFH concept. We therefore do not expect a rapid transition away from the consumer behaviors associated with COVID-19. The industrial and commercial demands will strongly depend on the economic recovery, which may lead to a longer-term change in the total electricity demand.

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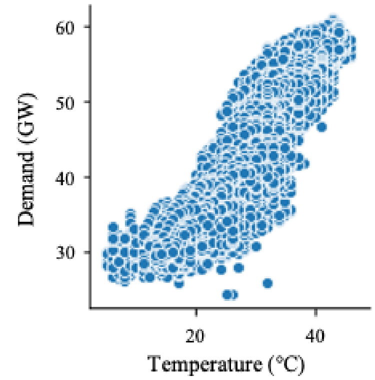

Figure 8: KSA electricity demand and Riyadh city temperature data for 2019.

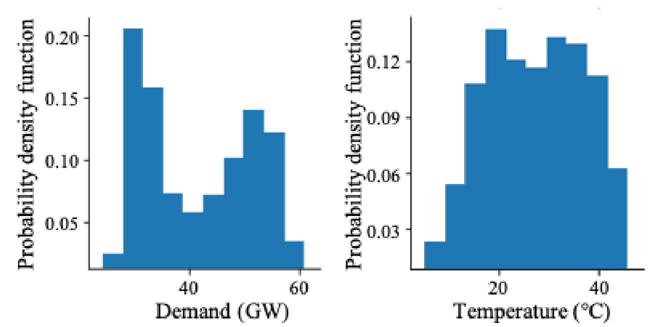

Figure 9: Probability density function of the electricity demand of KSA and the temperature data of Riyadh city for 2019.

Appendices

Appendix A: Datasets

This section describes the two datasets used in our case study: the electricity demand and ambient temperature of the KSA.

A.1. Electricity Demand Data

The electricity demand data used in this study represent the aggregate demand of the KSA measured from the generation side, spanning 4.5 years from January 1, 2016, to June 30, 2020. The data for 2020 encapsulate all of the imposed social distancing policies (from school closures on March 8 until end of curfew on June 21). Figure 9 (left) shows the histogram of the electricity demand for the most recent complete year (2019). We observe two components in the histogram, where the first represents the winter demand and the second represents the summer demand.

A.2. Ambient Temperature Data

Similar to the electricity demand data, we obtained the ambient temperature data from January 1, 2016, to June 30, 2020. The data were collected from three weather stations located in three major cities, each having the highest population in its operational area. The station coordinates and the cities are: (1) Riyadh [24.75°N, 46.75°E], (2) Jeddah

[21.50°N, 39.25°E], and (3) Al-Ahsa [25.23°N, 49.35°E]. The histogram of Riyadh's ambient temperature in 2019 is shown in Figure 9 (right). Furthermore, Figure 8 shows the scatter plot of the electricity demand (y-axis) and the temperature (x-axis). The figure shows clearly the linear correlation between the electricity demand and temperature.

Appendix B: Linear Correlation Coefficient

We used the linear correlation coefficient to measure the linear dependency between the electricity demand and temperature as follows:

$$\rho(X, Y) = \frac{\mathbf{Cov}(X, Y)}{\sqrt{\mathbf{Var}(X)\mathbf{Var}(Y)}},$$

where X and Y are random variables and **Var** and **Cov** are the variance and covariance, respectively. Values closer to a *linear correlation coefficient* of 1 or –1 indicate a strong linear association between X and Y. A value of 1 represents a perfect direct relationship between the variables X and Y, while a value of -1 indicates a perfect inverse relationship between these variables. A value of 0 indicates that no correlation exists between these variables.