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Impact of COVID-19 interventions on electricity power production: An empirical investigation in Kuwait

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1. Introduction

The outbreak of Coronavirus Disease 2019 (COVID-19) has impacted almost all aspects of life globally, adding pressure on the medical sector, leading to closures in the educational sector, and affecting the commercial sector’s viability. The industrial sector is of no exception with experts raising concerns about the COVID-19 pandemic impact on electricity supply chain [1–4]. With the enforcement of lockdown restrictions across several countries around the globe, electricity demand has been fluctuating, with early evidence suggesting a reduction in the production of electricity from the energy sector [5–7]. Therefore, governments around the world, including Middle East and North Africa (MENA) and Gulf Cooperation Council (GCC) countries, have implemented emergency action plans with the help of field experts and researchers to address concerns about how and when COVID-19 might impact electricity power production [8–15].

Energy consumption changed amid the COVID-19 outbreak [16–18]. Jiang et al. [19] and Zhong et al. [20] overviewed COVID-19’s impact on energy demand and consumption, where Abdeen et al. [21], Rouleau and Gosselin [22], Ruan et al. [23] and Zanocco et al. [24] reported high correlation between electricity consumption and the number of infected people, social distancing range, and residential and commercial activities level. Chen et al. [25] surveyed the utility power consumption bills during the month of February and reported approximately 50% of the residents experienced higher electricity use than average, whereas 40% estimated their electricity consumption to be about the same. Ruan et al. [26] found higher fluctuation in electric demand and prices compared to electricity power production. Cheshmezangi [27] extended the survey to May 2020, where he observed an average increase of of 67% (February 2020), 95% (March 2020), 35% (April 2020), and 22% (May 2020) in electricity energy costs compared with similar time periods in 2019. These results matched the IEA [28] reports about the increase in residential energy consumption due to the pandemic lockdown measures and changes in social activities. Similarly, Akrofi and Antwi [15] and Snow et al. [29] exhibited an increase in electricity consumption in the residential sector in Africa and Australia, respectively, while the COVID-19 outbreak situation was further examined by Edomah and Ndulue [30] under three scenarios (i.e., no lockdown, partial lockdown, and full lockdown) in Lagos, Nigeria. Compared with the industrial and commercial sectors, the residential sector’s electricity consumption increased by up to 7.8% relative to the no lockdown case. In addition, during the post-pandemic and no lockdown period, a relative increase in the total power consumption (about 3.86%) was observed, which was...
mainly driven by the increase in electricity demand in the commercial sector (increased by 9.3%). However, the full lockdown measures decreased the total consumption by up to 2.3%, while partial lockdown had no significant effect on the electricity demand. Despite the sector-level analysis, the study overlooked the impact of varying the number of curfew hours on electricity production. Bahmanyar et al. [31] compared the electricity consumption levels with respect to the different lockdown measures implemented in Europe. Countries with severe COVID-19 cases (i.e., Spain, Italy, Belgium, and United Kingdom) and extreme lockdown restrictions showed a significant reduction in the weekday energy demand by up to 25%, whereas countries with less restrictions (i.e., Netherlands) exhibited less reduction (up to 11.6%) compared with the same period in 2019. Nevertheless, electricity consumption has relatively increased by up to 2.1% in countries with no lockdown policies such as Sweden. In fact, the weekday electricity demand increased by up to 8.2% compared with weekend’s demand of 2019 (similar to Santiago et al. [32] findings for Spain). Although this study implied that people activities might affect the energy production during a major crisis, it was limited to the statistics of one specific date of the previous year (2019) without controlling for dynamic variables (e.g., meteorological, population, GDP index, among other factors). Garcia et al. [33] estimated the aggregated levels of COVID-19 lockdown on electricity consumption based on a clustered customer behavior profile using Smart Meter data in Spain. The findings showed that residential electricity consumption increased to approximately 15% and 7.5% during full lockdown and post-pandemic periods, respectively. Whereas, the consumption of non-residential customers decreased to 3% and 14.5% during full lockdown and post-pandemic periods, respectively. Whilst this study integrated a customer behavior factor in electricity consumption, it was limited to only one town/region and it overlooked the hourly effect of curfew type variation (partial vs. full) on energy usage. Aruga et al. [34], Elavarasan et al. [35], and Ali et al. [36] investigated the effect of the lockdown measures on the power consumption in India and Pakistan. Despite the non-uniform reduction in power consumption during COVID-19 lockdowns (about 14% to 24%), they concluded that the energy consumption was recovered as the quarantine constraints were relaxed. However, the energy recovery rate was correlated with the household’s economical income. Therefore, special policies and economical aid were recommended for the poorest two regions (i.e., Eastern and North-Eastern regions). These studies were limited to short-term data sampling whereas the pandemic’s effect was changing with time. As for China, one of the world’s top energy consumers and the place where the first COVID-19 case was reported [37], Norouzi et al. [38] numerically evaluated the electricity demand during the time of the pandemic, controlling for key variables related to the COVID-19 outbreak (i.e., GDP growth, infected people index, epidemic severeness index, and export income, among other trading economical factors). The results showed that the reduction in electricity demand (about 21%) during the pandemic was due to the rigid conventional electricity sources that might have also penalized the energy efficiency and power distribution systems. In other studies, López Prol et al. [39], Agdas and Baroah [40] and Werth et al. [41] included additional control variables such as meteorological data and stringency index [42] (i.e., a measurement for quarantine and facilities closure reactions) to assess the electrical load production in Europe and USA. The results showed a cumulative drop in electricity production that ranged between 4% to 13% within the four months following the lockdown measures with a steep declination rate in daily electrical load (up to 20%) as governmental responses tightened. Lu et al. [43] further extended the accuracy and stability of the electricity demand predictions using multi-objective optimization. However, the black-box model (i.e., artificial neural network) used in both studies [38,39] might fail to explain the physical and socioeconomic reasons and conditions behind the variation in the energy demand. Moreover, the aforementioned studies excluded curfew hours from their analyses.

Understanding the impact of the COVID-19 pandemic and its containment measures on electrical load production is of great importance to policymakers since it equips them to address potential disruptions in electricity power production. This work aims to evaluate the impact of the COVID-19 pandemic and various lockdown policies on hourly electrical load levels. These research questions are addressed using advanced regression analysis and longitudinal data from 2015 to 2020 that cover various time periods: Pre-pandemic, post-pandemic without curfew, partial lockdown with varying curfew hours, and full lockdown periods. This paper contributes to the literature by offering an in-depth view of the impact of various COVID-19 quarantine measures on electricity power production using longitudinal data that covered one of the longest and most versatile lockdown periods in the world (lasting over six months with various levels of curfew hours). This approach is the first attempt that allows an in-depth examination of the impact of COVID-19 pandemic and various lockdown measures on electricity production levels in the State of Kuwait.
2. Background and context

2.1. Electricity supply chain

The State of Kuwait is located in Western Asia, covering a total land area of nearly 18,000 km². The climate in Kuwait is characterized by extremely hot and dry weather during most of the year. The average maximum monthly temperatures range between 37 °C to 45 °C (98 °F to 113 °F). Kuwait depends heavily on fossil fuels, including natural gas, heavy fuel oil, and crude oil, to generate electrical power through steam, gas, and combined power cycles. Around 60% of the power generated is by steam turbine cycles and the remaining 40% is generated by gas turbine cycles [44]. The gas turbines are used in emergencies and during times of peak load. There is only one renewable power plant (Shyghaya station) that produces almost 0.02% of the total power in Kuwait. However, it is expected to generate 15% of total power production by 2030 (10 MW from solar modules, 10 MW from wind power, and 50 MW from solar collector power). Currently, nine power stations, including the renewable energy plant, generate a total electrical power of 7,980,224 MWh. About 10% of the total electrical power generated is utilized internally for water desalination and auxiliary power demand [45]. Table 1 lists the total capacity of each power station, while Table 2 shows the tariffs of electricity for each sector set by the government of Kuwait. Table 2 demonstrates the heavily subsidized cost of electricity in Kuwait (approximately 8% of GDP) [44]. There are more than 60 production units of electric power distributed across the power stations, 26,000 electric transformers located across the country with 33,000 km of electrical medium voltage (MV) cables, and 36,000 km of electrical high voltage (HV) overhead power transmission lines. Figure 1 illustrates the power supply chain in Kuwait from the natural resources to the customer’s household.

To be noted that electricity consumption in Kuwait matches electricity production levels [46,47]. This is mainly due to the use of a “Pull” system where electricity production in Kuwait is matched with forecasted demand in a given time period. This is achieved by diverting the hot steam in power plants to produce fresh water in the adjacent desalination plants (i.e., multi-stage flash (MSF) distillation process) [48]. In addition, electricity storage technology is unemployed currently in Kuwait. Thus, most of the produced electricity is generated to match the exact demand. Therefore, the data, methods and results of the electricity supply chain is only presented in term of electricity production.

2.2. COVID-19 political and economical context

The COVID-19 pandemic impacted both the political and economical context in Kuwait. In terms of the political context, new mandates were issued to enforce partial and full lockdown policies. Unlike some countries that implemented soft lockdown measures (i.e., shelter-in-place orders meant that people were “advised” to stay at home and reduce their activities outside of home), Kuwait implemented hard lockdown measures where movement was restricted to various degrees depending on the enforced lockdown policy (e.g., partial vs. full lockdown). These lockdown policies were accompanied by laws that punished people who violated the lockdown orders with financial fines and/or imprisonment [49]. Law enforcement agents patrolled residential areas to enforce the lockdown policies and apprehend any violators. The economical situation was also influenced by the pandemic where the majority of businesses were forced to shutdown during various phases of the pandemic. This included private businesses (e.g., restaurants, cafes, gyms, shopping malls, etc.), governmental entities (e.g., ministries, public transportation, parks and beaches, etc.), and educational entities (e.g., private and public schools, colleges, and universities). Thus, these closures and lockdown policies were associated with an increase (a decline) of up to 46% (90%) in mobility within the residential (retail and recreation) sector, respectively, over the time period from February 24, 2020 to August 7, 2020 as shown in Fig. 2 [50].

3. Data and methodology

The average hourly electrical load data (in MW) were collected from the National Control Center (NCC) at the Ministry of Electricity and Water (MEW) in Kuwait [45]. The data included 49,320 observations, covering the time period from January 1, 2015 to August 16, 2020. This measure was operationalized as the primary dependent variable, denoted LOAD_i,j (where i and j represent the day of measurement and the hour of measurement, respectively). Studying this outcome is of great importance since it is related to (1) the availability of electricity (i.e., if peak load exceeds the capacity of the electrical network, then power outage could result), (2) economical costs (given the subsidized price of electricity as demonstrated in Table 2), and (3) environmental costs (given that electricity in Kuwait is generated mainly by burning fossil fuel [51]).

For the main predictors, the pandemic-related news was tracked from the official daily announcements published by Kuwait’s Ministry of Health (MOH) [52] and Kuwait’s Center for Government Communications (CGC) [53]. Using these announcements, a post-pandemic indicator (POST_i) was constructed, which is a dummy variable that is equal to one if the date of introducing the first COVID-19 case in Kuwait (i.e., date of measurement ≥ February 24, 2020), zero otherwise. This factor was considered because it is expected to be associated with changes in electricity production levels, as suggested by Roidt et al. [54]. Table 3 summarizes the different time periods observed in this study.

A curfew hour indicator (CURFEW_i,j) was also created, which is a dummy variable that is equal to one if curfew was enforced during the hour that the electricity data was measured (i.e., hour j of day i), zero otherwise. This variable allows us to examine the effect of enforcing curfew hours on the average hourly electrical load. Similar to POST_i indicator, the pandemic-related news were tracked from the official daily announcements published by MOH and CGC to construct the CURFEW_i,j variable. The aforementioned factor was selected because it is expected to be associated with changes in power generation as suggested by López Prol et al. [39] and Hale et al. [42].

The average daily temperature (TAVG) in Kuwait was controlled for using climate data from Peterson and Vose [55] and EPA [56], which include daily temperature measurements (in °C) from two weather

| Table 1 |
| --- |
| **Total capacity of power stations in the State of Kuwait [45].** |
| **Station** | **Electrical power (MWh)** |
| 1 | Shuwaikh Station | 12,037 |
| 2 | Shuaiba North Station | 536,213 |
| 3 | Shuaiba South Station | 372,740 |
| 4 | Doha East Station | 402,650 |
| 5 | Doha West Station | 1,115,772 |
| 6 | Az - Zour South Station | 2,369,276 |
| 7 | Sabiya Station | 2,164,848 |
| 8 | Az - Zour North Station | 1,002,953 |
| 9 | Shyghaya Station (renewable) | 1,735 |
| **Total** | | **7,980,224** |

* Electrical energy statistical report for the month of June 2020.

| Table 2 |
| --- |
| **Tariffs of electricity cost in the State of Kuwait [45].** |
| **Sector** | **Cost ($ per kWh)** |
| Residential | 0.0065 |
| Commercial and investment | 0.0164 |
| Governmental | 0.0818 |
| Agricultural | 0.0164 |
| Industrial | 0.0164 |

* $1 = 0.3067 Kuwaiti Dinar (K.D.).
stations located in Kuwait international airport and Hawalli governance, respectively. These weather stations were approximately 10 km (6 miles) apart and shared similar elevation levels. The TAVG was defined as the average of the two daily average temperature measurements obtained from the two stations. This factor was considered to control for potential climate effects where more electricity is expected to be consumed as the average temperature rises (i.e., electrical load is expected to increase during hotter days).

The effect of the month of measurement (MONTH) was also controlled for using 2nd degree polynomial terms to account for the inverted U-shaped monthly curvilinear effect found in the raw data (see Figure 3). Finally, a set of dummy variables was constructed to control for non-observed temporal fixed effects (FE), which includes year FE (e.g., population growth) and day-of-week FE (e.g., weekday versus weekend effect). Additional controls for a 3rd degree polynomial effect of hour-of-day (HOUR), which ranges from 0 to 23, was also considered to account for within-day curvilinear temporal effects (see Figure 4). Finally, the interactions between the curvilinear effects of hour-of-day (HOUR) and the constructed post-pandemic (POST) and curfew hour (CURFEW) indicators were controlled for to examine potential changes in the hourly effects during post-pandemic periods with and without

### Table 3

| Time period       | Dates (dd/mm/yy) | Curfew hours | No. of curfew hours | Period length (in days) |
|-------------------|------------------|--------------|---------------------|------------------------|
| Pre-pandemic      | Before 24/02/20  | None         | 0                   | —                      |
| Post-pandemic (no curfew) | 24/02/20 - 23/03/20 | None         | 0                   | 27                     |
| Partial lockdown I | 22/03/20         | 5 PM - 4     | 11                  | 15                     |
| Partial lockdown II | 06/04/20         | 5 PM - 6     | 13                  | 34                     |
| Full lockdown     | 10/05/20         | All day      | 24                  | 21                     |
| Partial lockdown III | 30/05/20       | 6 PM - 6     | 12                  | 21                     |
| Partial lockdown IV | 20/06/20        | AM           | 3                   | 9                      |
| Partial lockdown V  | 21/06/20        | 7 PM - 5     | 10                  | 9                      |
| Partial lockdown VI | 29/06/20       | 8 PM - 5     | 9                   | 28                     |
| Partial lockdown VII | 30/06/20      | 2 PM - 9     | 6                   | 33                     |
curfew enforcement. Observations with missing daily temperature measurements were dropped, resulting in a total of 48,312 hourly observations. Table 4 includes summary statistics of the main variables.

A multilevel regression model with random intercepts [57,58] was used to examine the statistical relationship between the average hourly electrical load (LOAD$_{ij}$), the main pandemic-related predictors (POST$_{i}$ and CURFEW$_{ij}$), and the control variables specified above. A multilevel approach allows for the examination of changes in the average hourly electrical load both within a day (level-1) and between days (level-2). The econometric specification for the level-1 component of the multilevel regression model is given by:
LOAD_i; = \pi_0 + \pi_1 \text{CURFEW}_i + \sum_{k=1}^{3} r_{i,k} \text{POST}_k \times \Gamma_{i,k} + u_{0i}
+ \epsilon_i
\tag{1}

where \(i\) and \(j\) denote the measurement day and hour of LOAD, respectively, and \(\epsilon_i\) is the within-day (level-1) random error where \(\epsilon_i \sim N(0, \sigma^2_{\epsilon})\). The econometric specification for the level-2 component of the multilevel regression model is given by:

\[
\pi_{0i} = \pi_{00} + \pi_{01} \text{POST}_i + X_i \Gamma_{02} + u_{0i}
\pi_{1i} = \pi_{10} + \pi_{11} \text{POST}_i, m \in \{2, 3, 4\}
\pi_{3i} = \pi_{30} + \pi_{31} \text{POST}_i, w \in \{5, 6, 7\}
\tag{2}
\]

where \(X_i\) is a vector that includes the remaining control variables \((\Gamma_{02}\) is a vector of regression coefficients that are multiplied by the control variables in \(X_i\), and \(u_{0i}\) is the between-day (level-2) random error (allows the intercept of LOAD to vary randomly across days) where \(u_{0i} \sim N(0, \sigma^2_{u})\). Combining Eqs. (1) and (2) yielded the following mixed model:

\[
\text{LOAD}_{ij} = \gamma_{00} + \gamma_{01} \text{POST}_j + X_{ij} \Gamma_{02} + \text{CURFEW}_{ij} + \sum_{k=1}^{3} r_{j,k} \text{POST}_k \times \Gamma_{j,k} + u_{0j} + \epsilon_{ij}
\tag{3}
\]

An alternative variant of the above model was also considered by taking the natural logarithm of \(\text{LOAD}_{ij}\). This approach allows for the examination of the relationship between the explanatory variables and the percentage of change in the outcome variable and addresses potential skewness in the distribution of the outcome variable. The econometric specification of the mixed logged model is given by:

\[
\ln(\text{LOAD}_{ij}) = \gamma_{00} + \gamma_{01} \text{POST}_j + X_{ij} \Gamma_{02} + \text{CURFEW}_{ij} + \sum_{k=1}^{3} r_{j,k} \text{POST}_k \times \Gamma_{j,k} \times \text{CURFEW}_{ij} + u_{0j} + \epsilon_{ij}
\tag{4}
\]

These models were estimated using the PROC MIXED procedure in SAS software [59], with the Maximum Likelihood (ML) estimation method [60].

4. Results and discussion

The results of estimating regression models (3) and (4) are presented in Table 5. These models were used to assess the post-pandemic and curfew effects on average hourly electrical load (henceforth hourly load). Figure 5 shows the parity plot based on the results of regression model (3), which suggests that the majority of predicted values were within ±10% of actual observed hourly load levels. Controlling for other variables, the results of model (3) suggest that there was an average decrease of approximately 675 MW (\(p < 0.01\)) in the hourly load during the baseline hour (i.e., 12 AM) of the post-pandemic period with zero curfew hours (henceforth post-curfew period) compared with the pre-pandemic baseline level. The post-pandemic effect varied depending on the hour-of-day as indicated by the statistically significant interaction terms between the post-pandemic indicator and the polynomial terms of hour-of-day (i.e., \(\gamma_{21}, \gamma_{31}, \text{and } \gamma_{41}\)). Despite these variations, the hourly load levels during the post-pandemic period were consistently below pre-pandemic levels, as illustrated in the top row of Fig. 6. The differences between the pre-pandemic (top left) and post-pandemic (top right) lines in Fig. 6 ranged between approximately 400 MW to 1100 MW depending on the time of day (the difference was minimum at 3 PM and maximum at 11 PM).

The hourly load levels during the post-pandemic curfew periods (i.e., partial and full lockdown periods) were consistently below pre-pandemic levels, as illustrated by the bottom row of Fig. 6.
Nevertheless, differences in hourly load were not always evident between the partial/full lockdown periods and the post-pandemic period. For instance, there was no statistical significant difference between the lockdown periods and the post-pandemic period at the baseline hour (12 AM) as indicated by the statistically insignificant coefficient of $\gamma_{10}$. However, the curfew effect varied across the hours-of-day as indicated by the statistically significant interaction terms between the curfew indicator and the polynomial terms of hour-of-day (i.e., $\gamma_{40}$, $\gamma_{50}$, and $\gamma_{60}$). Thus, the differences in the hourly load were examined between the post-pandemic period and the full lockdown period, and the results showed a statistically significant curfew effect that led to a further decline of approximately 463 to 667 MW ($p < 0.05$) in hourly load during curfew time periods from 12 PM to 8 PM (compared with post-pandemic levels). Moreover, differences in hourly load were examined between the post-pandemic period and the partial lockdown period with 12 curfew hours (where curfew was enforced from 6 AM to 6 PM). The results presented no statistically significant differences between hourly load levels except for the time periods between 6 PM and 8 PM, where a statistically significant curfew effect was found, leading to a further decline of approximately 463 to 569 MW ($p < 0.05$) in hourly load. These results suggest that the curfew effect was most evident during peak load hours.

The results of regression model (4) mirrored the previous results as shown in Table 5 and Figure 7. First, the hourly load declined by an average of 12.1% ($p < 0.01$) during the baseline hour of the post-pandemic period (compared with pre-pandemic levels). Differences in hourly load levels between the post-pandemic period and the pre-pandemic period ranged from a 9.0% post-pandemic decline (at 9 AM) to a 14.0% post-pandemic decline (at 11 PM). Second, the hourly load levels during the partial and full lockdown periods were consistently below pre-pandemic levels, as illustrated by the bottom row of Figure 7. Third, differences in hourly load between the post-pandemic period and the full lockdown period were most evident during the time period from 12 PM to 7 PM, where a statistically significant curfew effect was found, leading to an additional 4.6% to 6.0% decline in hourly load ($p < 0.05$). Finally, differences in hourly load between the post-pandemic period and the partial lockdown period were statistically significant at the time period from 6 PM to 7 PM only.

These findings support evidence that the demand for electricity declined post the COVID-19 outbreak (even when there was no curfew enforced) as found locally and globally by Alhajeri et al. [61], Al-Abdullah et al. [62], Abulibdeh [63] and Edomah and Ndulue [30], Bahmanyar et al. [31], Elavarasan et al. [35], respectively. This can be explained by the post-pandemic decline in electricity demand due to the closures of businesses, public sector agencies, and schools [30,39,63]. Moreover, the enforcement of partial and full curfew policies further reduced power consumption. When people stay at home, it is expected that electricity consumption would increase, especially for necessary appliances and lighting. However, air conditioning (which is the primary electricity consumer in the residential buildings in Kuwait) might not contribute to the expected increase in electricity consumption since it is always in operation even when people leave home [44]. In addition, more people in Kuwait stayed at home during the summer time (June to August 2020) due to travel bans, which might further increase the electricity demand in the residential sector for the same reason mentioned before. However, the expected increase in electricity consumption in the residential sector was compensated by the net decrease in electricity demand in the remaining sectors, mainly driven by the reduction in electricity consumption in the commercial and governmental sectors [30]. Unlike the context studied by Edomah and Ndulue [30] where they observed a relative increase of 3.86% in electricity consumption in the commercial sector post-pandemic (with no curfew), the immediate closure polices in Kuwait led to electricity demand reduction of up to 14.0% in the post-pandemic period (with no curfew) compared with pre-pandemic levels.

5. Conclusions and policy implications

This paper analyzes the impact of COVID-19 containment measures on electricity power production in the State of Kuwait. An empirical
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investigation was conducted to assess the impact of various lockdown measures on load production levels over one of the longest and most versatile COVID-19 lockdown periods in the world (lasting over 6 months and ranging from partial lockdown with varying curfew hours to full lockdown). The analysis used hourly longitudinal data and multi-level regression models to examine changes in electricity production levels, respectively, over the time period from 2015 to 2020. The research design used in this study has multiple advantages. First, the use of longitudinal (rather than cross sectional) data allows for examining changes in electricity production levels over time, which yields a better understanding of how and when production levels change. Second, the inclusion of five years of pre-pandemic data allows for isolating potential pandemic effects (e.g., curfew policies) from non-pandemic effects (e.g., changes in the temperature, population growth, and other monthly and yearly temporal effects). Third, the use of a multilevel framework allows for investigating changes in electricity generation levels both within a day (i.e., hourly effect) and across days (i.e., other temporal effects that vary across days) using both fixed and random effects. Finally, the variety and length of the lockdown periods allow for a detailed examination of electricity supply chain changes in response to changes in curfew policies—mimicking a quasi-experimental design. The study yielded the following conclusions:

- Electricity power production during post-pandemic periods decreased by up to 16.4% compared with pre-pandemic levels (potentially due to the closure of commercial and governmental sectors).
- The decline in electrical load varied within the day (depending on the hour-of-day) and across days (depending on lockdown policies).
- Electricity production declined by approximately 9.0% to 14.0% during the no curfew post-pandemic period compared with pre-pandemic levels.
- Curfew enforcement was associated with a further decline in electricity power production up to 16.4%, but only during peak load hours (i.e., 12 PM to 6 PM), as indicated by statistical tests that

![Fig. 6. Post-pandemic effect on predicted average hourly electrical load in MW changes for pre-pandemic, post-pandemic (no curfew), partial lockdown, and full lockdown time periods.](image)

* Baseline level: 12 AM pre-pandemic

(a)
indicate the significance of the curfew enforcement further declines at the 5% level.

The findings of this study can help policymakers understand the impact of a global health pandemic (such as COVID-19) on electricity supply chain, understand economic (e.g., impact on electricity subsidy cost) and environmental (e.g., impact on CO₂ emissions resulting from electricity production process) implications of such changes, and how and when the demand for electricity would be influenced by lockdown measures. The predictions can also help policymakers take precautionary measures on an hourly basis during natural disasters. Furthermore, the results can help policymakers understand how to influence electricity demand during seasons when electricity load reaches capacity of power plants (e.g., during summer season) to avoid potential power outbreaks. For example, policymakers may adopt working-from-home policies in governmental agencies to reduce electricity demand by alleviating the high electricity consumption needed to cool down governmental buildings during peak days when power outbreaks are expected to occur.

Despite the thorough longitudinal multilevel analysis of the data in this work, future research could benefit from sector-level analysis, which was omitted in this work due to data collection limitations, to further examine changes in electricity demands across the residential, commercial, industrial, and agricultural sectors. In addition, within-sector analysis could explore whether policymakers can use electricity load data as a real-time indicator of (a) the impact of the pandemic on economic activity (e.g., decline in electrical demand in the commercial sector due to recession) and (b) the compliance of people with lockdown orders (e.g., whether people follow stay-at-home orders). Future research could also benefit from examining the impact of COVID-19 containment measures on other outcomes of interest (e.g., fuel supply chain, environment, economy, etc.) with different contexts (e.g., other regions with different climates and energy subsidy structures).

Fig. 7. Post-pandemic effect on predicted average hourly electrical load in % changes for pre-pandemic, post-pandemic (no curfew), partial lockdown, and full lockdown time periods. (Cont.).
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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