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Analysing the impact of lockdown due to the COVID-19 pandemic on the Indian electricity sector

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ABSTRACT

This paper aims to understand the responsiveness of the power sector during the lockdown due to the COVID-19 pandemic beginning from March 25, 2020 and analyses its impact on the demand, operation and supply of electricity in the Indian power system. The role of the C&I load share in reducing the electricity demand of the different states in India has been examined using multi-sectoral regression analysis. The impact of the pan India lights-off event on the short-term operational flexibility response of the power system has also been analysed using high-temporal resolution data. The results indicate that there has been a reduction of nearly 70 TWh of electricity demand during the lockdown period, an 11 % reduction compared to 2019. The top three states recording the highest reduction were Maharashtra, Gujarat and Tamil Nadu at 11 TWh, 10.6 TWh and 8.4 TWh, respectively. Regression analysis revealed that out of the total drop in load demand — 73 % is owed to the industrial sector, while the remaining 27 % is to the commercial sector. This demand drop also impacted the upstream electricity supply mix where 96 % of the reduction in supply was borne by the coal generating units, recording its lowest national plant load factor at 35 % with a 16 % reduction in overall CO2 emission compared to the same period in 2019. In conclusion, a case study of Maharashtra has been used to analyse the impact of this reduction in electricity demand on the supply mix, hourly load profile and cost of supply under the different lockdown phases.

1. Introduction

Ever since the initial outbreak of the novel Coronavirus (2019-nCoV) in late December 2019, which was first reported from Wuhan, in China’s Hubei province, it had spread to 212 other countries and territories, affecting more than 102 million people and claiming over 2 million lives as on January 31, 2021 [1]. The Indian government imposed a stringent lockdown starting from March 25, which lasted for 68 days. The timeline is summarised in Appendix A of the Supplementary section. A recent study based on the ‘Google COVID-19 Community Mobility Reports’ reveals that throughout India, ‘retail and recreation, grocery and pharmacy, visits to parks, transit stations and workplace’ mobility dropped by — 73.4 %, −51.2 %, −46.3 %, −66 % and − 56.7 %, respectively, during the first two lockdown phases [2].

The consumption of electricity is a key indicator of the overall functioning of the economy [3]. The total demand for electricity in India is segregated into the following sectors: industrial (30 %), agricultural (21 %), residential (29 %), commercial and traction load (13 %), and public services (7 %) [4,5]. The state-wise breakup of the sector-wise demand for electricity is shown in Appendix B of the Supplementary section. More than half of the country’s demand for electricity comes from the C&I sectors, which were adversely affected during the lockdown phase [6]. Analysing the trends in electricity consumption will help power system planners, operators, regulators, and policy framers make informed decisions and corrective actions in case of such extreme events in the future [7]. The International Energy Agency reported that the pandemic would shrink India’s demand for electricity by at least 5 % in 2020–21 [8].

Therefore, this paper analyses the impact of the lockdown on electricity demand, given the heterogeneity of sectoral load share in different states in India. In addition, this analysis is also extended to study the impact of sudden load changes on the power system flexibility. The impact on the supply of power and the change in the electricity power system,
generation mix as a causal effect of the reduction in demand is also analysed. Along with the reduction in energy and peak demand during the strict lockdown phase, the resultant load curve shape has undergone significant changes prompting both the IEA and Bloomberg to claim that ‘weekdays resemble prolonged Sundays’ [9].

1.1. Global reduction in the demand for electricity

Table 1. summarises the impact of COVID-19 on the reduction in the demand for electricity in major countries around the world.

1.2. Aim of the study, research gaps, and novelty

The lockdown due to COVID-19 posed several challenges to the global economy as a whole and the power sector in particular. Therefore, this paper is an attempt to answer the following questions that confront the power sector:

• What is the impact of the different phases of lockdown on demand for electricity in different states in India?
• How does the Indian power system cope with the short-term variability in load demand and its impact on operational flexibility?
• What is the impact of the reduction of end-use demand on the supply mix, especially on the coal units’ PLF and associated emissions?

Table 1
Impact of COVID-19 on the reduction in the demand for electricity in comparison to 2019.

| Continent  | Country | Period of analysis | Demand for electricity compared to 2019 | Comments | Ref. |
|------------|---------|--------------------|----------------------------------------|----------|-----|
| North America | USA     | 22 Mar –30 Apr     | 9 % to 13 %                             | New York-ISO and Midcontinent-ISO experienced the most severe reduction in demand. | [10–13] |
|            | USA     | 22 Mar –30 Apr     | 9 % to 13 %                             | Southwest Power Pool (SPP) and Electric Reliability Council of Texas (ERCOT) had the least reduction. | |
|            | Canada  | 11 Mar–14 Jun      | 14 %                                   | Demand was reduced by 10 % in Ontario and 5 % in Alberta, British Columbia, and New Brunswick. | [14,15] |
| South America | Brazil | 22 Mar–30 Apr     | 19 %                                   | Southern Brazil recorded the highest reduction in demand. | [16] |
|            | Argentina | 22 Mar–30 Apr  | 26 %                                   | Amongst the Latin American countries, the highest reduction was observed in Peru and the lowest in Chile. | [17] |
|            | Bolivia | 22 Mar–30 Apr     | 29 %                                   |                                             | |
|            | Chile   | 22 Mar–30 Apr     | 6 %                                    |                                             | |
|            | Peru    | 22 Mar–30 Apr     | 32 %                                   |                                             | |
|            | • Colombia |            | 14 % to 16 %                           |                                             | |
|            | Ecuador | 22 Mar–30 Apr     | 14 % to 16 %                           |                                             | |
|            | Panama  | 22 Mar–30 Apr     | 14 % to 16 %                           |                                             | |
|            | Uruguay | 22 Mar–30 Apr     | 14 % to 16 %                           |                                             | |
| Europe | • Austria | 150 days from lockdown | 5 % to 14 %                           | The UK experienced the highest average reduction. | [18–22] |
| Europe | France  | 150 days from lockdown | 5 % to 14 %                           | Sweden did not impose any lockdown and resulted in a slight increase in energy demand. | |
| Europe | Hungary | 150 days from lockdown | 5 % to 14 %                           |                                             | |
| Europe | Italy   | 150 days from lockdown | 5 % to 14 %                           |                                             | |
| Europe | Poland  | 150 days from lockdown | 5 % to 14 %                           |                                             | |
| Europe | Sweden  | 150 days from lockdown | 5 % to 14 %                           |                                             | |
| Europe | UK      | 150 days from lockdown | 5 % to 14 %                           |                                             | |
| Europe | Ukraine | 150 days from lockdown | 5 % to 14 %                           |                                             | |
| Europe | Germany | 17 Mar–31 May     | 8 % to 10 %                            |                                             | [23] |
| Europe | Spain   | 14 Mar – 30 Apr   | 13.5 %                                 |                                             | [24] |
| Asia      | Turkey  | 1 Mar–30 Jun      | 16.5 %                                 | The highest reduction in electricity demand was observed in May. | [25,26] |
| Asia      | Pakistan | 1 Apr–9 May      | 15 %                                   | Reduction in demand till February followed by an increase of 0.7 % and 4.6 % in April and May, respectively. | [27] |
| Asia      | China   | 1 Jan–31 May     | 7.8 %                                   |                                             | [28–31] |
| Bangladesh |        | 26 Mar–31 May     | 16 % to 18 %                           | The highest reduction in electricity demand was observed in mid-April. | [32] |
| South Africa |        | 26 Mar–10 May    | 18.6 %                                 | Philippines, Malaysia and Singapore recorded a reduction of 30 %, 23 % and 8 %, respectively. | [33] |
| South-east Asia | 23 Mar–30 Apr  | 8 % to 30 % |                                             |                                             | [34] |
| Australia |        | 1 Jan–17 Aug     | 6 % to 8 %                             | The maximum reduction observed in New South Wales is followed by Queensland, Tasmania, Victoria, and South Australia. | [35,36] |
Previous studies which are highlighted in Section 1.1, primarily dealt with an aggregate analysis of the reduction in the demand for electricity due to the pandemic without delving into the details of the trends in demand for electricity in different phases of the lockdown. This is the first attempt to establish a relationship between the severity of the lockdown and the reduction in the demand for electricity using multivariate regression analysis.

For the first time, the reduction in demand for electricity has been attributed to sector-specific electricity consumption in all the twenty-eight states and one union territory of India; all have different electricity consumption patterns. The impact of reduced demand on the generation mix that is predominated by the coal fleet and on its PLF has been ascertained. In addition, the reduction in power sector emissions due to the reduction in supply from the existing coal fleet has been estimated.

The role of hydropower as a dispatchable power source, which provides the necessary flexibility during the lights-off event, has also been established. Lastly, using the case study of India’s largest electricity-consuming state, Maharashtra, and its capital, Mumbai, an attempt has been made to determine the change in the shape of the load curve and its impact on hourly emission and cost of electricity supply.

1.3. Article structure

In this paper, Section 2 delineates the overall framework of the analysis and sources of data. Subsequently, Sections 3, 4 and 5 answer the questions in Section 1.2 on demand, operational flexibility and supply of electricity, respectively. Section 3 discusses the impact of the lockdown on the electricity load demand. It also establishes the role of the commercial and industrial sectors in the reduction of load demand. Section 4 shows the resilience and operational flexibility of the regional grids to mitigate short-term demand variability. This section also highlights the present role of hydropower in India as the primary source of flexibility. Section 5 presents the impact of the lockdown on the supply of electricity, especially on the existing coal fleet and its associated emissions. Finally, Section 6 uses the case study of Maharashtra to quantify the change in the load curve shape, the hourly emission and the cost of electricity supply. Section 7 concludes the paper.

2. Material and methods

This section delineates the overall framework that is chosen to analyse the impact of the lockdown on the Indian power sector, as shown in Fig. 1. The first step involves fixing the period of analysis, which in this case is 160 days, beginning from March 25 to August 31, 2020; this involves four periods of intense lockdown, followed by three subsequent unlock periods.

Next, the impact of this lockdown on load demand for each Indian state is estimated from the daily electricity demand data that is supplied by POSOCO [37], which is then aggregated to get an overall estimate for India. Thereafter, this change in the load demand compared to the same period in 2019 is correlated with the individual state’s sectoral electricity load demand and its sectoral share in India’s GDP, following which suitable conclusions are drawn.

The sectoral impact on load reduction is ascertained using multivariate regression analysis. This portion also involves analysing the impact of flexible hydropower in mitigating abrupt demand fluctuation during the pan-India lights-off event using high temporal resolution (minute interval) data. It quantifies the region generation resource flexibility in India using a suitable metric.

Subsequently, the impact on the supply of electricity due to demand disruption is analysed, emphasising the PLF and emissions of coal power units. Further, the impact of this demand disruption in the change in the load shape and its effect on the hourly electricity cost and emissions are analysed using hourly electricity demand data of India’s largest electricity-consuming state, Maharashtra.

3. Impact on demand for electricity during different phases — National and state level

3.1. National electricity demand reduction

Analysing the data supplied by POSOCO [37] and comparing it with that of 2019, the total reduction in load demand in India during this...
period was found to be 70 TWh, as shown in Fig. 2(a). It is about 11% of the electricity demand during the same period in the previous year. In fact, after the first two weeks of the lockdown, the electricity demand was reduced by nearly 23%. By the end of Unlock-2, the peak and energy demand reached the pre-lockdown levels, which indicates the resumption of most industries and commercial establishments, as shown in Fig. 2(b).

The daily energy and peak reduction trend was similar, as shown in Fig. 3(a), with the highest reduction in both peak and energy demand reaching 31% in comparison to 2019 on March 27 and April 27, respectively. The average energy and peak demand reduction during the four lockdowns and three unlock phases is shown in Fig. 3(b). A gradual decrease in average energy and peak demand is observed in the subsequent lockdown phases, indicating increased electricity consumption.
contributed primarily by the C&I sectors with increased relaxation in the lockdown norms.

3.2. State-wise electricity demand reduction

The state-wise reduction in the demand for electricity in the four phases of the lockdown is illustrated by Fig. 4. Out of the 70 TWh reduction in load demand during the lockdown phase, 38% occurred solely in the western region contributed mainly by the states of Maharashtra (16.2%) and Gujarat (15.7%); the northern and southern regions recorded a similar reduction in demand of 26% each followed by the eastern region and north-eastern region with 9% and 0.7% respectively.

Amongst the states and the union territories, the highest reduction in demand occurred in Delhi (NCT), Maharashtra, Tamil Nadu, and West Bengal in their respective northern, western, southern and eastern regions. Incidentally, these are also among the worst affected states in terms of case fatality rate as of August 31, 2020 [38].

Observations reveal that four (Maharashtra, Gujarat, Tamil Nadu and Uttar Pradesh) out of the twenty-eight states in India which share nearly 50% of the country’s combined C&I load share, had a net load reduction of just above 50% of the total load reduction. The trend in energy and peak demand reduction in the major states in India is illustrated in Appendix C and D in the Supplementary section.

3.2.1. Impact of lockdown on C&I sectors

As per the data published in late August by the NSO, India witnessed its greatest contraction of GDP by 23.9% in the April–June period, which is the highest among all the G20 economies [39]. Amongst the major industries, mining, manufacturing and construction were the
worst hit, whereas the impact on electricity, gas, and other utilities was relatively less. Following the slump in the economy, the unemployment rate peaked at 23.5% in April. As per the latest estimates from the Centre for Monitoring Indian Economy (CMIE), out of the 86 million salaried employees in India, which comprises nearly 22% of the total employment, 21 million lost their jobs between April–August 2020 [40]. Loss of jobs and livelihood led to the exodus of migrant workers and their families to their home states, many died in transit although no

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**Fig. 4.** The share of the reduction in demand for electricity compared to 2019 in the four lockdown phases.
official data has been released by the Indian government. In an answer to a question in the Lok Sabha (the lower house of the Parliament), the Minister of State for Labour and Employment revealed that at least 10.5 million people had returned to their home states, mainly Uttar Pradesh, Bihar, and West Bengal [41]. Therefore, this chain of events and a lack of industrial and commercial activity prompted a reduction in the demand for electricity.

In India, electricity is one of the eight core industries which also include coal, crude oil, natural gas, refinery products, fertiliser, steel, and cement which taken together comprises 40 % weight in the Index of Industrial Production (IIP) which is a metric published monthly by the NSO to estimate the growth rates of various industries in India. The production of coal is also closely associated with the generation of electricity as almost 70 % of India’s coal consumption is attributed to the power sector [42], both of which dipped during the lockdown [43].

As previously mentioned, nearly 52 % of India’s demand for electricity comes from the C&I sector, which was either shut down or operated with limited capacity in staggered shifts during the initial phases of the lockdown. The challenges faced by the industries include limited availability of transportation facilities, productivity loss due to lack of remote working facilities, limited availability of staff, inadequate supply of raw materials and low demand from consumers. Amongst the energy-intensive designated consumers, as per the provisions of the Energy Conservation (EC) Act 2001, the production of cement and steel declined by 32.2 % and 42 %, respectively [43]; the production of textile slumped by 15 % [44]. The only silver lining being the production of fertilisers, which increased by a meagre 3.9 %. The shutdown of educational institutes and offices, as well as the scant availability of transport facilities, reduced the demand for the pulp and paper industry by at least 15 % [45]. The automobile sector which depends on imports from China for nearly 27 % of its components [46], is a key indicator of the economy saw a slump in production by 80 % and lowering of sales by almost the same number [47]. Overall exports also plunged by 30 %. Overall, the GVA from the industrial sector (secondary sector) reduced by 38.1 % in Q1-FY-21.

Amongst the services sectors, aviation and hospitality were the worst hit. The Indian aviation sector suffered a revenue loss of 85 %, with a potential job loss of nearly 3 million [48-50] while the hospitality industry’s revenue slumped by 39 %–45 % in comparison to 2019 [51,52]. Indian railways, which consume nearly 1.5 %–2 % [53] of the annual demand for electricity, saw a slump of 99 % in passenger and 13 % in freight loading with an overall 42 % loss in revenue [54]. The collection of the Goods and Services Tax which is a consumption-based tax and is also an essential indicator of consumer demand for goods and services plunged to a record low of 72 % in April in comparison to the previous year only to recover by 4 % in September [55]. Overall, the GVA from the service sector (tertiary sector) reduced by 20.6 % in Q1-FY-21.

Analysis of the individual states in the previous section suggests that the reduction in load demand was not uniform across all states and this can be attributed to the sector-specific electricity consumption of the individual state. The most prosperous states in terms of GDP lie in the southern, western and northern regions, contributing 30 %, 28 % and 26 % to India’s overall GDP, respectively. Incidentally, these regions recorded the bulk of the load reduction (almost 90 %) during the lockdown. The relatively poor states belong to the eastern and north-eastern regions, contributing merely 13.4 % and 2.6 % to India’s overall GDP, respectively. The combined reduction in load demand in both these regions is only 10 %. Therefore, this correlation between the reduction in load demand and the contribution of the C&I sectors in this demand reduction is analysed in the subsequent section using multivariate regression analysis.

3.2.2. Multivariate regression analysis

During the initial phase of the lockdown, this reduction in demand could solely be attributed to the closure of the industrial and commercial sectors. In line with progressive relaxations, as more and more industries were allowed to reopen, starting from labour-intensive to energy-intensive, this relationship between the reduction in the demand for electricity and its associated contribution to the C&I load was gradually decoupled, as seen in Fig. 5. Additionally, occasional outliers were observed in the later phases due to erratic weather. Such outliers were seen in the case of Uttar Pradesh in phase-3 of the lockdown when a hailstorm ravaged 15 of its districts and killed at least 29 people [56]. The situation was similar in West Bengal in phase-4 of the lockdown due to the super-cyclone, ‘Amphan’ [57]. As previously mentioned, there exists a significant correlation between electricity demand in the C&I sectors and the GVA share of the secondary and tertiary sectors to individual state’s GSDP; there ought to be a similar correspondence between the reduction in the demand for electricity with secondary and tertiary sector’s contribution to the GSDP as shown in Fig. 6.

By modelling the overall percentage reduction in the demand for electricity due to the sectoral (agricultural, commercial, industrial and residential) electricity consumption using multivariate regression analysis, the C&I sectoral electricity demand was found to explain (on the basis of R² value) 90 % of the reduction in electricity demand and resulted in the following equation:

\[
\Delta_{\text{Dem}} = 0.75 \times I_i + 0.35 \times C_i \forall i \in \text{states}
\]

where \(\Delta_{\text{Dem}}\) is the percentage reduction in demand for electricity in the state ‘i’, \(I_i\) and \(C_i\) are the sectoral percentage share of the industrial and commercial demand for electricity in the ith state respectively. Eq. (1) suggests that the industrial load share contributes more than double the commercial load share in the overall reduction in the demand for electricity during the lockdown phase.

Table 2 illustrates the coefficients of \(I_i\) and \(C_i\) during different phases during the entire lockdown and unlock period. A gradual reduction in the value of \(R^2\) in the subsequent phases and in particular during the later unlock phases indicates that there is a greater variance in the value of the dependent variable, that is, \(\Delta_{\text{Dem}}\) which cannot be precisely explained by the independent variables, that is \(I_i\) and \(C_i\). Averaging across different periods reveals that nearly 73 % of the entire load reduction was from the industrial sector, while the remaining 27 % came from the commercial sector. No such definite correspondence was observed when the reduction in demand was compared to the agricultural and domestic sector’s electricity consumption, as shown in Appendix E and F in the Supplementary section. This again affirms that the reduction in the demand for electricity is primarily due to the shutdown of the secondary and tertiary sectors.

To illustrate the above statement with an example, it could be assumed that under normal conditions, state ‘i’ has a forecasted load demand of 1000 units during the lockdown period, and its aggregate share of the C&I load is equal to 50 % (that is, the industrial and commercial load demand being 40 % and 10 % respectively). Results from our analysis indicate that during the lockdown, the estimated load reduction comes out to 33.5 % (that is, 335 units), of which the industrial sector contributes 30 % and the remaining 3.5 % is contributed by the commercial sector. Therefore, a higher proportion of C&I load demand will result in a greater reduction in the load demand in the individual states. As seen in Fig. 7, the estimated reduction from Eq. (1) closely follows the actual reduction with an average error of ± 0.4 %. However, certain outliers are observed in the estimated results, for example, Uttar Pradesh and West Bengal, which have a higher reduction than estimated mainly due to erratic weather conditions during phases 3 and 4 of the lockdown.

4. Short term operational flexibility of the Indian power system

4.1. Impact of the pan-India lights-off event on resident load demand

On April 3, the Indian Prime Minister, in a televised address to the
nation, made a clarion call to the citizens to turn off the lights in their homes on April 5. Citizens were requested to instead light candles, torches, or flashlights for nine minutes at 09:00 p.m. as a mark of solidarity and unity to overcome the crisis of COVID. The system operator, POSOCO, was confronted with the challenge of maintaining grid stability and voltage control. From past estimates of load demand and the rural and urban domestic consumer base, POSOCO inferred that the demand would reduce by 12–13 GW in only two to four minutes and recover after nine minutes [58].

However, the event saw an overwhelming response from the people, and the actual load was reduced by 31 GW, which was more than double what POSOCO had anticipated. Therefore, India’s overall demand dropped by 12–13 GW in only two to four minutes and recover after nine minutes [58].

4.1.1. Impact on power system flexibility

Power system flexibility refers to the ability of the power system to cope with variability and uncertainty due to sudden changes of load demand and renewable energy output simply by matching demand with supply within a short period without violating any system constraints [60]. The rate at which a power plant changes its output, which is often denoted by the percentage of its rated capacity per minute, is called its ramp rate [61]. The ramp rate of thermal power plants depends on their size, age, and mode of operation and it is one of the major impediments for flexible operation of the power system. [62–66]. In India, the typical ramp rates for coal power units vary between 0.5 % and 1.5 % of their capacity or Maximum Continuous Rating (MCR) per minute, whereas hydro and gas units are at least 3–5 times higher than coal. The CEA prescribes ±3/5 % MCR/min for central coal-generating units. Moreover, the CERC, in its latest tariff notification, began to incentivise or penalise any deviation of ramp rates from 1 % MCR/min [67].

The entire exercise of matching the reduction of load demand due to the lights-off event in such a short span of time was successfully conducted by POSOCO by leveraging the flexibility of the hydropower plants; operating the thermal units at their technical minimum levels; disconnecting the wind power plants to maintain frequency within the specified limits; disconnecting all capacitor banks at substations and putting into service all reactors to absorb excess reactive power in order to maintain the voltage within the specified limits.

The average all-India demand ramp-down rate for the initial 20 min (between 20:49 hrs and 21:09 hrs) was found to be around 1460 MW/min, with an instantaneous peak of 4196 MW/min. The average ramp-
The regional generation mix within that one hour of abrupt load cut-off event was characterized by a significant decrease in generation rates across different regions. The highest instantaneous generation ramp-up rate for the next 20 min (between 21:10–21:30 hrs) was 1140 MW/min. with an instantaneous peak of 3016 MW/min. It is worth noting that the highest instantaneous generation ramp-down rate for the different regions was: NR-1594 MW/min., WR-1049 MW/min., SR-1667 MW/min., ER-528 MW/min., and NER-94 MW/min, which is significantly higher than the experiences encountered by POSOCO in the past [68].

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change from 20:30 hrs to 21:30 hrs reveals the overall short-term flexibility provided by hydropower, as shown in Fig. 9. The riparian northern and eastern regions provided the maximum hydropower flexibility. In contrast, the relatively arid western region used the existing thermal capacity (both coal and gas) for the necessary dynamic load response. High temporal resolution data from the western regional load dispatch centre (WRLDC) revealed that the minimum load demand occurred simultaneously across all states at 21:09, as shown in Fig. 10.

4.1.2. Modelling and analysis

By utilising the high temporal resolution data that is supplied by POSOCO, we now define a normalised metric \( \text{Flex}^{+/−} \) to quantify the net upward/downward operating flexibility that is provided by a generating source as shown in Eq. (2) [69]:

\[
\text{Flex}_{s}^{+/−} = \frac{\max|\text{Gen}_{s}, t| - \min|\text{Gen}_{s}, t|}{\text{Op.Cap}_{s}} \forall s \neq \text{renewables(excludinghydro)}
\]

where \( \max|\text{Gen}_{s}, t| - \min|\text{Gen}_{s}, t| \) is the maximum rate of change of output by the resource ‘s’ per unit of its maximum operating capacity.

As seen from Table 3, hydro offers the highest flexibility among all other sources followed by gas. Renewable sources are excluded since these are non-dispatchable unless curtailed in order to maintain grid stability and assume must-run status in India as per the provisions of IEGC, 2010 [70].

We also define a critical ratio, \( \rho \) as shown in Eq. (3):

\[
\rho = \frac{\text{Flex}_{\text{hydro}}^{+/−}}{\sum_{s \neq \text{hydro}} \text{Flex}_{s}^{+/−}} \forall s \neq \text{hydro, renewable}
\]

which is the ratio that quantifies the role of hydropower as a flexible resource as compared to other sources such as nuclear, coal, and gas which are either run as baseload plants or as dispatchable sources.

5. Impact of the reduction in electricity demand on electricity supply

5.1. Impact on coal power plants

Compared to 2019, the total electricity generation was reduced by nearly 53 TWh during the entire lockdown phase and an additional 15.3 TWh during the first three unlock phases, as seen in Fig. 11. Coal thermal power plants accounted for more than 96% of the total reduction in supply. Due to the higher average cost of supply and reduction in demand, the generation from the coal-based units of the state and the private sector were reduced more than that of the central sector, as shown in Fig. 12.

The plant load factor (PLF) of a conventional power source is the
Table 3
Flex$^{+/-}$ in each region for different resource types.

| Region   | Nuclear | Coal | Hydro | Gas | Critical ratio $\rho$ |
|----------|---------|------|-------|-----|----------------------|
| NR       | 0%      | 0%   | 9%    | 13% | 50%                  |
| WR       | 4%      | 3%   | 10%   | 6%  | 61%                  |
| SR       | 9%      | 14%  | 7%    | 11% | 74%                  |
| ER       | 0%      | 0%   | 7%    | 11% | 93%                  |
| NER      | 0%      | 0%   | 15%   | 13% | 61%                  |
| Overall  | 6%      | 6%   | 8%    | 7%  | 61%                  |

Fig. 10. Demand profile in the western region during the lights-off event at 21:00 hrs on April 5, 2020.

Fig. 11. Daily generation mix from 1 March to 31 August (a) 2020 (b) 2019.
ratio of its actual generation to its maximum possible generation within a specific time interval, as shown in Eq. (4) [71]. Similarly, for non-conventional renewable power plants, it is known as the plant’s capacity utilisation factor (CUF).

\[
PLF_i = \frac{\text{Actual generation}}{\text{Maximum possible generation}} \times \frac{1}{\text{Specified time interval}}
\]

and \( s \in S \neq \text{renewables} \)

\[
\text{Maximum possible generation} = \text{Rated capacity} \times \frac{1}{\text{Specified time interval}}
\]

The average PLF of the coal units, which before the lockdown hovered above 50 %, reduced to 38 % immediately after the initiation of the lockdown, and it recovered only by the end of the Unlock-2 phase, as shown in Fig. 13. A steady decline in the coal PLF with the reduction in load demand is observed in Fig. 14, reaffirming that the coal power plants primarily contributed to the supply reduction.

Out of the 74 TWh of reduction in the generation from coal, the western region accounted for nearly 40 %, followed by the southern and northern regions with 30 % and 23 %, respectively. Following the reduction in generation from coal, the generation from hydro and gas increased, with gas reaching a plant load factor of 26 %, which was around 20 % in 2019. Curtailment of renewables due to lack of demand and poor wind speeds [72] has reduced electricity generation from wind and solar resources by about 3 % from 2019 [73].

5.2. Impact on power sector emission

A decrease in conventional power generation during the pandemic has resulted in a drastic improvement in air quality and pollution levels worldwide as well as within the country [74–79]. Out of India’s 2.2 Gt CO\(_2\) emissions in 2018, nearly 51 % is attributed to the electricity sector [80]. Using CEA’s latest CO\(_2\) baseline database for thermal power plants in India as shown in Table. 4, the avoided CO\(_2\) emission during the 160 days of lockdown was found to be around 86 Mt. It amounts to a 16 % reduction compared to the same period in 2019. From January 1 till August 31, the global CO\(_2\) emission from the power sector decreased by 555 MtCO\(_2\). The US accounted for the highest reduction at 133 MtCO\(_2\).
coal consumption during the 160 days of lockdown and unlock phase has reduced by 16%, similar to the previously found reduction in CO₂ emissions. Therefore, the lockdown has not only abated 86 MtCO₂ emissions but has also saved nearly 51 Mt of valuable coal resource.

6. Case Study—Maharashtra

This section explores the impact of lockdown on India’s largest electricity-consuming state, Maharashtra, using hourly supply data from DISCOM. There has been a substantial change in the generation mix in Maharashtra, accounting for 13% of India’s demand for electricity, as shown in Fig. 17 [83]. Both the energy and peak demands contracted by 14.6% and 13.1%, respectively, compared to 2019. The load duration curve for 2020 is steeper than that of 2019 during the same period, which subsequently reduces the effective operating hours of the mid-merit power plants, which increases their per-unit cost of generation.

The share from the central thermal generating stations has increased due to its relatively lower per-unit ex-bus ACoS (INR 2.95/kWh) when followed by the European Union and India at 94 MtCO₂ and 85 MtCO₂, respectively, as shown in Fig. 15.

The emission from the power sector decreases as load demand reduces during the lockdown, as shown in Fig. 16. This is due to the significant decrease in generation from the dispatchable state and private sector coal power plants. Appendix G in the Supplementary section depicts the trend in coal consumption (including imported coal) by the thermal power plants in India. It reveals that both domestic and imported coal consumption decreased in 2020 compared to 2019. Overall emission from the power sector in 2020 compared to 2019 is shown in Table 4.

### Table 4

Weighted average emission factor for conventional power plants in India [81].

| Fuel Type          | Emission Factor (tCO₂/MWh) |
|--------------------|---------------------------|
| Coal               | 0.98                      |
| Lignite            | 1.37                      |
| Gas & Diesel       | 0.48                      |

The trend in CO₂ emissions is also shown in Fig. 15. During the lockdown, daily CO₂ emissions from different regions are shown. The decrease in demand during the lockdown has reduced CO₂ emissions in all regions, with the most significant reduction seen in China (12 MtCO₂). The share of central thermal power plants in India has increased due to its relatively lower per-unit ex-bus ACoS (INR 2.95/kWh) when compared to 2019.
compared to the state (INR 4/kWh) and private (INR 3.94/kWh) owned counterparts. The generation from the seven state-owned coal power plants of Maharashtra and their associated ex-bus ACoS can be seen in Fig. 18. Units that have a higher ex-bus ACoS are turned down in favour of cheaper units. The share of renewables, wind and solar in the mix has remained the same as in 2019 at nearly 9% despite a 5% increase in capacity, primarily due to low wind speed resulting in a low generation [84].

6.1. Impact on the load profile

The change in the shape of the normalised hourly average load curve during successive phases of the lockdown of Maharashtra’s capital, Mumbai, is illustrated in Fig. 19. The 2020 load curve resembles a typical residential load profile in summer, with a peak at midnight, mainly attributed to the residential space cooling requirement. The evidence for the lack of industrial and commercial activity is reflected in the load curve profile, which appears to be much flatter during the otherwise peak noon period in the initial phase of the lockdown and approaches the profile that corresponds to the previous year only after the lockdown. There is hardly any discernible difference between a weekday and a weekend during the lockdown period and resembles the weekend pattern of 2019. This justifies IEA’s claim that ‘weekdays resemble prolonged Sundays’ [9].

6.2. Impact on hourly cost and emissions

A reduction of 14.6% in demand for electricity in the state resulted in a 12% and 30% decrease in the total ex-bus ACoS and emissions, respectively, compared to 2019, as shown in Fig. 20. Despite such low demand, the cost of power procurement for the state’s DISCOM, which covers nearly 85% of the total electricity distribution in the state, has been found to increase by over 20% in comparison to 2019 from INR 3.7/kWh to INR 4.5/kWh; this is mainly due to the portion of fixed charges that is compulsorily payable to the state GENCO.

The shape of hourly average emission intensity and cost of supply
curve closely represent the net load curve, defined as total load demand minus the sum of non-dispatchable generations, i.e. wind and solar. However, there is a distinct contrast between the shape of emission and the cost of supply curves during the pandemic compared to the previous year. Unlike the previous year, during the lockdown phase, the peak emission and cost of supply occurs during the evening when the residential load demand is maximum and the generation from solar and wind are at their lowest.

7. Conclusion

Overall, this study presents an overarching post-facto analysis of the impact of the COVID-19 pandemic on the Indian power sector. The generalised modelling framework proposed in this paper can be applied to any country or region to identify the specific sectors contributing to the demand reduction, given that sectoral load share and demand reduction are known. The impact of the COVID-19 pandemic has been felt globally, and it has impeded economic growth and mobility. India imposed an initial strict lockdown in four successive phases of sixty-eight days and three subsequent unlock phases of ninety-two days. This paper uses data of high temporal granularity from various sources such as the national system operator POSOCO, regional and state load dispatch centres, several reports from the Ministry of Power, the Central Electricity Authority (CEA), national and state economic surveys, etc. to evaluate the impact of lockdown measures on the Indian power sector. In this context, the following conclusions can be drawn from this study as answers to the questions referred to in Section 1.2:

- Question 1: What is the impact of the different phases of lockdown on demand for electricity in different states in India?

During this initial lockdown phase, the peak demand reduced by 30% compared to 2019. The load demand reduced by nearly 70 TWh during the 160 days of lockdown and unlock phases which is about 11% of the electricity demand during the same period of 2019. The highest reduction was observed in Maharashtra at 16.2%, followed by Gujarat at 15.7% and Tamil Nadu at 12.3%. Uttar Pradesh, West Bengal and...
A strong positive correlation is observed between the share of C&I demand for each state in India using multivariate regression analysis. A sector-wise electricity consumption and the reduction in the electricity demand in the US, UK and other European countries. This is in line with the results obtained from studies in the US, UK and other European countries.

This paper formulates the relationship between the share of the sector-wise electricity consumption and the reduction in the electricity demand for each state in India using multivariate regression analysis. A strong positive correlation is observed between the share of C&I load and the reduction of electricity demand. This analysis further reveals that both C&I load shares contribute to the reduction in electricity demand, although disproportionately. States that have higher industrial load share witnessed greater load reduction.

- Question 2: How does the Indian power system cope with the short-term variability in load demand and its impact on grid flexibility?

The pan-India lights-off event on April 5 revealed that hydropower plants in the riparian states provided the bulk of the flexibility. A normalised flexibility metric \( \text{Flex}^{+/-} \) based on the rate of change of electricity has been formulated to quantify the flexibility that is provided by each source of dispatchable power generation. It reveals that different regions in India respond quite differently to sudden load variations in the electricity grid which is based on its available resource mix. The pan-India lights-off exercise reveals that the Indian grid is presently overly dependent on hydropower as a source of flexibility, providing nearly 60 % of the flexibility support, followed by gas at 25 %. Coal and nuclear provide the least flexibility.

Managing the drop in demand was handled smoothly by POSOCO as it was known ex-ante. Hydropower energy capacity being constrained by their monthly budgets and, above all, gas being presently unavailable, the existing coal power plants need operational and structural modifications so that they can operate with greater flexibility (lower MCR, higher RR, lower start-up/shut down time) as the penetration of variable renewable energy (VRE) increases. In light of this, additional storage capacity will be required to mitigate the variability and uncertainty of VRE generation for India to achieve its ambitious target of 450 GW of VRE capacity by 2030 with generation from VRE exceeding 30 % (presently in 2020 around 10 %) [68]. VRE resources, along with storage, needs to provide both frequency and voltage support as ancillary services. At present, there is no cost-based market mechanism that can incentivise state-based GENCOs to remunerate the procurement of such ancillary flexibility services [85]. The recently implemented Real-Time Market (RTM) on June 1, 2020, aims to ease the demand-supply mismatch and will be beneficial in the long term with additional VRE capacity [86].

Delhi occupies the fourth, fifth and sixth places at 7.2 %, 6.6 % and 5.5 %, respectively. This is in line with the results obtained from studies in the US, UK and other European countries.

Question 3: What is the impact of the reduction of end-use demand on the supply mix, especially on the coal units’ PLF and associated emissions?

On the supply side, low demand prompted several small, costly state coal units to shut down. The bulk of the supply reduction was borne by the coal fleet, nearly 96 %. A steady decline in coal PLF from 55 % to 35 % and net CO\(_2\) emissions by 16 % or 86 MtCO\(_2\) in comparison to 2019 was observed during this period. Overall consumption of coal has declined by 16 % compared to 2019, leading to 51 Mt of coal resource savings. Therefore, an 11 % reduction in electricity demand during lockdown resulted in a 16 % reduction in CO\(_2\) emission and coal consumption compared to 2019. However, this only translates to a marginal reduction in emission intensity of the grid from 0.73 kgCO\(_2\)/kWh to 0.68 kgCO\(_2\)/kWh owing to the simultaneous reduction in overall demand.

Lastly, along with changes in the generation mix, there has also been a change in the consumption pattern, as is evident from Maharashtra’s daily load duration curve and particularly in the urban agglomeration of Mumbai. The share from cheap central coal stations had increased compared to the costly state and private units. There is hardly a discernible difference in the electricity consumption pattern between weekdays and weekends during this lockdown period. The reduction of electricity demand during the lockdown has had its share of advantages and disadvantages for the Indian electricity sector. Its advantages include:

- The lockdown period in India has significantly improved air quality, pollution levels and reduced greenhouse gas emissions from the power sector with 86 MtCO\(_2\) abatement, which is 16 % less than in the similar period of 2019.
- It has resulted in significant fuel resource-saving of around 51 Mt of coal, 8.5 % of India’s annual coal consumption in the power sector.
- It has led to higher trading volumes in the Indian electricity market (IEX, PXIL). GENCOs sold their excess power to the DISCOMs or open access (OA) consumers at a relatively lower market-clearing price [87]. It has resulted in savings of INR 102 million for the consumers (DISCOMs/OA consumers), less than 23 % compared to 2019. The operation of the day-ahead market (DAM) in the IEX during the lockdown phase is compared with that of 2019 and is further illustrated in Appendix H of the Supplementary section.
- From an operational point of view, the hourly load curve assumes a much flatter shape during the initial lockdown phase, as seen in Fig. 19. Therefore, this makes the role of costly peaker plants virtually insignificant.
Finally, such events provide valuable lessons to system planners, operators, regulators, and policy framers to make informed decisions and corrective actions in case of such extreme events in the future. However, the reduction of demand during the lockdown also had its associated disadvantages on the Indian power sector, which include:

- From a climate perspective, even though there has been a significant reduction in load demand, the state GENCOs shifted their production to those coal units with a relatively lower ex-bus ACoS. Therefore this analysis has been extended to estimate the difference between the cost of supply for the GENCOs and revenue recovery by the DISCOMs from the previously obtained sectoral electricity consumption using the regression analysis, thus, quantifying the financial impact of lockdown on the Indian power sector [88].

**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.

**Appendix A. Supplementary material**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijepes.2022.108097.

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