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COVID-19 impacts on Indian power system planning and operation

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ABSTRACT

Governments around the world are implementing different measures like lockdown and stay-at-home orders to stop the spread of coronavirus amongst the common masses. It has caused electricity consumption to decrease and inverting the gap between demand and generation. Load-generation balance is maintained by shutting down or operating the fossil fuel generations at a low plant load factor due to must-run obligations over renewable generation. During lockdown periods, variable renewables' proportion in total energy consumption has reached record highs. The power system's inertia stability has decreased with displacement of conventional resources from generation schedule. It created new challenges for system operators to meet increased variability. New forecasting methodologies are adopted for modified peaks and shapes of the load curves. Power sector utilities are combating the issues of decreasing demand and liquidity caused by revenue shortfall. Cross-border restrictions on fuel imports are also affecting the portfolio of generation resources in long term. The ongoing pandemic is causing a paradigm shift in financial, political and technical aspects of power sector. This requires active engagement from government to help the sector thrive in difficult times and continue to work smoothly. In this context, this paper presents a comprehensive review of pandemic impacts experienced on power sector in the area of planning and operations. Also, inputs are provided from policy and operation perspectives to improve grid reliability and security during and post-event conditions. The fast implementation of demand side management programs is recommended to improve grid stability. Tariff restructuring, enhancing flexibility and incorporating consumer behavior in load forecasting have been suggested to have a more diversified and resilient power sector in the post-COVID era.

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1. Introduction

COVID-19 has wreaked havoc on the world economy. Due to the health crisis, governments around the world have implemented different measures to stop the spread of disease amongst the common masses. This ultimately led to the closure of public gathering places and lockdown with varied types of restrictions. Industries are forced to operate with limited staff and capacity. Normal business operations such as transport have been affected due to travel restrictions, work from home orders in a large number of organizations and closure of commercial shopping malls and restaurants due to social distancing. According to the International Monetary Fund, it is expected that global economy may decline by up to 3% and revenue loss of the tourism industry alone is around billion INR due to pandemic-related restrictions [1]. With tourism being a major driver of jobs and growth, impact of COVID resulted in huge job loss and deteriorated work quality in many Asia and the Pacific countries, as per International Labour Organization [2].

Several countries like European Union and USA experienced significant variations in consumption patterns. Italian power demand was recovering in the second quarter of 2020. But trend soon experienced a downfall due to the second wave of rising COVID cases in countries and tightened restrictions in the country. Great Britain experienced a sharp decline in electrical consumption of 11.4%. Even after relaxation in lockdown, it showed no signs of recovery. In France and Spain, the lockdown was implemented simultaneously across the country. France experienced a reduction of 20% in demand after the implementation of lockdown in country and is on the way to recovering pre-COVID consumption. Germany showed low initial decline rates as lockdown measures were implemented at different levels and times in states [3]. Government policies related to lockdown and closure of business activities, being implemented since March 2020, have affected the demand and supply of electricity across the world.

India has experienced a sudden drop in electricity demand due to the closure of industries and commercial establishments that
accounts to almost 50% of total electricity consumption in the country [4]. The reduction in peak demand has been experienced in all five electric grid regions of India. The quantum of reduction is estimated as 36%, 31%, 24% and 15% in western, northern, southern and eastern regions, respectively. The north-eastern region experienced a comparatively low reduction of 8.5% due to a lower share of industrial and commercial load in the total load of the region [5]. The Government of India (GoI) implemented nationwide series of lockdowns to curb the spread of infection in 2020: Janta Curfew (March 22), lockdown phase-1 (March 25–April 14), lockdown phase-2 (April 15–May 3), lockdown phase-3 (May 4–May 17) and lockdown phase-4 (May 18–May 31) [6]. Some of the lockdown restrictions included no large public gatherings, ensuring social distancing, the shutdown of schools and colleges and only essential activities were allowed. As the spread of disease came under control, various unlocks in the form of restricted lockdown took place in a phased manner in 2020: Unlock phase-1 (June 1–June 30), Unlock phase-2 (July 1–July 31), Unlock phase-3 (August 1–August 31), Unlock phase-4 (September 1–September 30), Unlock phase-5 (October 1–October 31) and Unlock phase-6 (November 1–November 30) [7,8]. As lockdown restrictions were eased in various unlocks, economic activities resumed. Though day restrictions were lifted outside containment zones, a night curfew was imposed. Public transportation was resumed with various precautions in place. The timeline of lockdown and unlock in India is shown in Fig. 1.

India experienced a 20% to 40% decline in demand under strict lockdown guidelines [9]. This decreasing trend reversed around May 2020 after lockdown phase-3. Residential demand recovered faster in comparison to industrial demand. The depreciation rate of energy demand has recovered from 22% to 17% [10]. The load curve has been modified due to pandemic, as a consequence, the power sector is facing a hard time maintaining load-generation balance. Utilities are focusing on generation mix as one of the key drivers for electricity cost optimization. A 9-minutes PAN India lights off event took place on April 5, 2020, to show solidarity with the volunteers in fight against the pandemic. This was the severest event with the largest ramping requirement over a short period in the history of the Indian system. The event was successfully handled with the help of available flexibility in Hydro and Gas generation. However, the event highlighted the need of increasing the share of flexible generation resources in the system to handle the high variability caused by the increasing penetration of renewables.

The power sector is one of the hardest-hit sectors with effects ranging from socio-economic to technical challenges. Power system challenges emanating from COVID created short-term, medium-term and long-term impacts on system operation and

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**Fig. 1.** Timeline of COVID-19 lockdown and unlock in India in 2020.
planning. Short-term impacts include the shutdown of costly generation facilities and a reduction in net revenue of utilities causing a financial crunch. Medium-term impacts account for stress in the distribution system due to a rise in residential demand, a boost in tariff rates to cover up for revenue losses, and cut-in costs of utilities, contributing to reliability issues. Reduction in baseload generation and decreased flexibility of power systems are seen as long-term impacts of pandemics on the power systems. The Indian power system was not immune to such sudden changes.

In March 2021, during the second wave of COVID-19, the impact on all India electricity demand was not significant, and it was higher by 22.8% y-o-y [11]. Despite such an increase in energy demand, power sector is still struggling to achieve higher Plant Load Factor (PLF) of thermal plants, fast deployment of renewable energy to fulfill the 175 GW target of 2022, recovery of revenue losses and enhancing system flexibility. In the post-COVID era, power system planning should be carried out as more assorted and resilient. Financial, political, and technical problems arising from ongoing pandemics require government support to get through difficult times. A study highlighted the impact of COVID-19 on the growth of renewable power capacity expansion in India demonstrating the delay in the under-construction projects due to disruption in supply and construction activities [12]. Another study analyzes role of Commercial and Industrial (C&I) sector load share in electricity demand reduction of the country [13]. Study shows a huge decline in steel, cement and textile production, Pulp and paper demand reduced due to closing of schools and shift towards online work culture. Production and sale of automobiles slowed down as a result of its reliance on imports. The C&I sector contributes almost 50% of total electricity demand that was operated within limited capacity due to productivity loss [13]. However, preparing a future plan to overcome all these challenges and identifying the critical ones that can be used as key learnings to tackle future similar events require a comprehensive review of COVID-19 impacts on complete power sector.

In this context, this paper investigates the impacts of the pandemic on the Indian power sector focusing deep down on the direct impact on electricity consumption, supply and revenue recovery, and some indirectly affected areas such as system planning and renewable energy transition. Sudden change in consumption pattern and generation resources has also affected the reliability and stability of grid. The proactive actions taken by utilities to mitigate the technical and financial risk and maintain supply reliability are highlighted in the study. The remainder of the paper is organized as follows: Section 2 discusses the impact from the perspective of electricity demand and revenue recovery for the Indian power sector. Section 3 describes COVID impacts on generation scheduling, voltage and frequency measures, ancillary services and electricity markets under system operation. Impacts related to system planning such as fuel availability, infrastructure development and renewable energy transition have been covered in Section 4. Section 5 provides future prospective recommendations for smooth operation of the power sector during the post-COVID scenario. Finally, Section 6 concludes the paper.

2. Overview of Indian power sector

The Indian power sector is demarcated into 5 electric grid regions: Northern Region (NR), Southern Region (SR), Eastern Region (ER), Western Region (WR) and North-Eastern Region (NER), for planning and smooth operations, as shown in Fig. 2. The inter-regional links help to achieve self-sustainable on a national basis. Presently, India has 113 GW of inter-regional transmission capacity which is anticipated to rise to 119 GW by 2022 [14]. The national grid of India is owned and maintained by transmission licensee Power Grid Corporation of India Limited (PGCIL) and operated by the independent system operator, Power System Operation Corporation (POSOCO), India. POSOCO is responsible for the integrated operation of the national grid in a reliable, efficient, and secure manner through its six control centers; one national and five Regional Load Dispatch Centres (RLDCs).

The total installed capacity of Indian power sector during COVID-19 was 370 GW (as on March 2020) out of which almost 62% share was the fossil fuel-based generation capacity, as shown in Fig. 3 [15]. At the regional level, India has a very diverse picture of generation mix with most of the electric demand and current generation capacity divided evenly between Northern, Western and Southern Regions. The northern region is rich in hydro and coal power generation. Eastern region has the largest coal reserve in the country and is dominated by coal based plants. Western region has largest electricity demand and maintains the highest share of coal and gas plant capacity. The majority of solar and wind plants are located in Western and Southern regions. North-eastern region has the highest hydropower potential in the country. With an aim of establishing a $47 billion reliable power supply and socio-economic development, India’s total electricity consumption is expected to increase almost 3 times in 2040 from its current level, prompting the need for large investments in generation and network infrastructure. However, COVID-19 has impacted both the operation of the exiting power systems and its future developments significantly.

3. COVID impacts on Indian electricity distribution sector

The Power Sector, being the backbone of all other sectors, is a major contributor to the country’s economy. It supplies round-the-clock electricity to all the sectors of the economy for their smooth working. During the pandemic, India has experienced a significant drop in demand. Besides demand variation, the load curve has deviated from its shape and is mimicking the weekend curve. However, reliable electricity supply has become a necessity to facilitate medical services and work-from-home needs under a stay-at-home policy. The changes in load patterns are affecting the operation and control strategies of the power system and subsequently system planning.

Indian distribution sector had various historical challenges which have been compounded during the pandemic era. Pre-COVID challenges include high Aggregate Technical and Com- mercial (AT&C) losses, revenue loss, subsidies, poor tariff setting, irregular customer tariff revision, delay in payment, etc. The inefficient operation of Distribution Companies (DISCOMs) can be attributed to policies centered around social welfare redistribution. These include poor tariff structure and its politicization, failure of regular tariff revisions that do not correspond to inflation and growing electricity procurement costs, high AT&C losses, and failure to get paid by the government as a consumers and subsidies providers. The impact of COVID on electricity sector will have a long-term impact on the overall economy of the country, majorly due to collapse of DISCOMs’ liquidity and their economic activity [16].

3.1. Electricity demand

Pre-pandemic electricity demand in India was undergoing the fastest growth within the world (averaging 6% per year) [17]. Reasons zeroed down were increasing industrialization, urbanization, rise in living standards, and various electrification goals. However, demand has experienced a dip due to the pandemic and implementation of measures to stop its spread. Lockdown caused demand reduction by 26.10% in terms of peak demand and 25.48% in terms of daily electricity demand in India [18].
3.1.1. Peak demand and load curve

The impact of COVID-19 on total, 15-minute block and peak demand is measured in terms of Percentage Demand Reduction (PDR) from the previous year week/weekend day of same month.

\[
PDR = \left( \frac{1}{n} \right) \times \sum_{i=1}^{n} \left( \frac{D_{ct}^i - D_{pc}^i}{D_{ct}^i} \right) \times 100
\]

Here, \(D_{ct}^i\) is the demand at time \(t\) during COVID period, \(D_{pc}^i\) is the demand at time \(t\) during pre-COVID period, and \(n\) is the total periods taken into consideration.

Fig. 4 presents PDR for peak hours during the lockdown period (23/03–29/03) as compared to the normal period (16/03–22/03) across the different regions of the country in 2020 [5]. The highest reduction is observed in the western region due to high industrialization and housing a significant part of the financial & commercial service sector of the country.

Fig. 5 presents statistics of regional PDR for each 15-minute block of lockdown period (23/03/20–29/03/20) as compared to pre-COVID period (16/03/19–22/03/19) across the different regions of the country. The highest block-wise PDR has occurred in NR as 41.5%, however one of its state (Punjab) faced block-wise PDR as high as 66.7%. In WR, the highest block-wise PDR of 51.67% occurred in Gujarat state. This may be due to high industrial and transport load in those regions.

Fig. 6 depicts the load profile of all India demand over different periods. As lockdown is implemented, the load curve deviated from its original shape in April, 2020. Differences in magnitude can be observed due to a decrease in economic and commercial activities. In August and December, as the intensity of restrictions on industries and economic activities eased, the load profile...
started tracing its previous shape. In August, demand reaches its value to the previous year 2019. Though in December, demand surpassed its magnitude in 2019, the increase in demand was less than the forecast. The peak demand of 180 GW in 2019 coincides with the forecast made using the Seemingly Unrelated Regression (SUR) model by Central Electricity Authority (CEA), but in 2020, an experienced peak of 173 GW was 8.4% lower than the predicted [20].

Owing to lockdown and work from home orders, a significant escalation in residential demand was expected. However, during the lockdown period from 23 March 2020 to 31 May 2020, urban households consumed less electricity in some parts of India. A survey is done by the Council On Energy, Environment and Water (CEEW) on a sample of households to investigate the reason behind an unexpected consumption pattern. Reasons encountered are required maintenance and malfunctioning of appliances, reduced household income amidst lockdown and fall in ambient temperature due to low pollution [21].

3.1.2. Sector-wise electricity consumption

Electricity consumption of each sector in India has increased continuously over the years, as shown in Fig. 7. Increasing population, rising income levels and rapid urbanization are responsible for increased demand in the domestic sector. The increased use of groundwater irrigation and electric tractors are pushing the pumping demand in the agriculture sector. The fuel switching to electricity such as induction cooking and penetration of electric vehicles is driving the increase in electricity demand in transport and residential sectors. The electricity demand in India is strongly driven by the industry sector with its share of approx. 43% in total electricity consumption of the country. Electricity consumed by the industry sector has increased 1.95 times in 2019–20 from its value in 2010–11. Due to the lock-down restriction, a significant drop, almost 5.4%, in industrial demand is expected in 2020–21 as compared to 2019–20. A similar trend of demand decrement due to COVID-19 is expected to be seen in transport sector also, majorly due to the limited number of railway runs. The impact of COVID-19 is expected to result in a 1.7% reduction in total electricity consumption in 2020–21 as compared to its value in 2019–20.

3.2. Total electricity supplied

Fig. 8 shows the total electricity supplied across five regional electricity grids of India on four days namely, March 4 and April 4, 2019 and March 4 and April 6, 2020 [22]. In March 2020, the electricity supplied to all regions was increased as compared to 2019 due to an increase in demand. However, a downfall in electricity supply is experienced in all regions due to lockdown implementation in April 2020. The reduction in overall electricity demand is met by hacking down coal-based plants due to must-run obligations over a renewable generation. This phenomenon can be analyzed from Fig. 9. The electricity generation from coal-based power plants is continuously increasing till the year 2018–19, however, started decreasing from 2019–20 onwards. In general, coal power plants provide necessary grid balancing. With a reduction in generation from coal, gas plant generation is increased to meet load and renewable variability. Renewable and nuclear generation is maintained at the pre-COVID level.

3.2.1. Cross-border power exchange

Indian grid is connected with Bangladesh, Bhutan and Nepal, under BBIN (Bangladesh, Bhutan, India, Nepal) sub-regional initiatives. Cross-border energy exchange amongst them amounts to around 15.6 TWh per annum. Nepal and Bangladesh meet their 42% and 9% of the peak demand, respectively through cross-border exchanges. Bhutan exports power generated by 95% of its installed capacity to India. During pandemic, Bangladesh achieved load generation balance by reducing generation from conventional sources instead of reducing energy imports from India due to competitive prices [18]. Nepal addressed the low demand by decreasing imports from India and operating hydro plants at a low level. Issues arising due to pandemic-related restrictions are taken care by cross-border links in the following ways [18]:

1. Providing flexibility through diverse generation resources.
2. Mitigating the problem of load restrictions by providing sufficient generation.

3.2.2. World’s severest ramping event: Light switch-off event

During the pandemic era, the Indian power system came across an event of high demand ramping within a short period. The PAN India lights off event occurred on 5th April 2020 at 9 pm for 9 min. It was announced by Indian prime minister Mr. Narendra Modi to show solidarity in terrible times. Amidst lockdown, peak demand in India was around 120–130 GW, where residential load contribution comprises of 10%–12% [23]. Sudden change in demand pattern impacts the grid frequency in the range of 49.5–50.2 Hz as specified in Indian grid code [24]. The anticipated reduction was estimated using the following methodologies to maintain the grid stability [25]:

**Overall Impact or Top-down Approach.** All India demand was mainly comprised of lighting load of household consumers between 18:00 h and 21:00 h as commercial and industrial load in the system were absent due to pandemic-induced countrywide lockdown since 25th March 2020. In the top-down approach, the demand reduction was estimated by calculating the household light load of the previous week same day. The obtained difference in the light load at these two times was approx. 11 GW.

**Granular Bottom-up Approach.** Total demand reduction at the grid level was calculated based on the number of household

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[Fig. 4. Peak hours PDR during the lockdown period (23/03/2020–29/03/2020) as compared to the normal period (16/03/2019–22/03/2019) [19].]

[Fig. 5. Statistics of regional PDR for each 15-minute block of (23/03/20–29/03/20) as compared to (16/03/19–22/03/19).]
consumers in India. Rural and urban household consumers’ data in India is considered from Saubhagya web portal. It was assumed that the load reduction of each rural and urban household consumer will be 50 and 100 Watts respectively (considering widespread use of LEDs). Demand reduction for the event was estimated to be 12 GW expecting the engagement of 80% households.

State Load Dispatch Centre (SLDC) carried out an individual analysis that estimated around 15 GW load reduction. After combining the results of all analyses, it was concluded that load reduction would be in the range of 12–15 GW. But the actual event experienced a load reduction of 31 GW, almost double the estimated amount.

The light-off event that happened on 5th April 2020 from 21:00 h for 9 min was managed by rescheduling of generation resources. Following observation could be drawn from event [25]:

1. The total reduction in demand recorded during the event was 31,089 MW.
2. All India demand experienced a decline from 20:45 h till 21:10 h.
3. Subsequently, at the end of event, demand started rising and settled at the value of 114,400 MW.
4. Grid frequency remained in the band of 50.26 to 49.70 Hz.
5. To match the ramping up and down rates associated with the event, thermal generation was replaced with hydro owing to its flexibility.
6. Hydro generation across the country escalated by 20:45 h.
7. Generation reduction of 17,543 MW (from 25,559 MW to 8,016 MW) was observed.
8. Again hydro generation was increased up from 8,016 MW to 19,012 MW till 21:27 h to balance an increase in demand after the event.

The event was successfully managed even when the estimated demand reduction was different from the actual event. Reasons for success can be attributed to the planning of extra reserve and system margin along with the scheduling of resources with good ramping characteristics.

3.3. Revenue recovery

Before COVID-19 pandemic, more investments and merchant projects were being conducted due to the dip in prices of solar and wind generation technologies. Sources of revenue for such projects were from spot and forward markets as compared to Power Purchase Agreements (PPAs). An ongoing pandemic changed the demand pattern causing a decline in power consumption. This increased the share of renewable generation in the total generation mix due to various policy support of GoI for their must-run operation such as renewable power obligation, feed-in tariff and waiver of interstate transmission charges. However, a report by CEA claimed that around 97.3 billion INR dues were by July 2019 from 24 GW of renewable energy production, as shown in Fig. 10 [26,27]. Tamil Nadu and Andhra Pradesh topped the list of highest DISCOM dues, followed by Telangana and Tamil Nadu [28]. Andhra Pradesh and Tamil Nadu combinedly account for approximately 50% of total due payments in RE-rich states. According to the Payment Ratification and Analysis in Power Procurement for bringing Transparency in Invoicing of Generators (PRAAPTI) portal, DISCOMs owe to GENCOs a total of 926 billion INR in February 2020. This would impact existing and upcoming PPAs with the likelihood of derailing the development of upcoming renewable projects. This can be a serious concern for investors relying on PPAs for investment recovery and making profits. Besides PPAs, people are facing difficulty in paying off the electricity bills due to increasing unemployment because of the pandemic. Government intervention reduced the negative financial impact on the sector and aided in the continuation of electricity services to all [29].

4. System operation

The COVID-19 pandemic is exclusive among the range of threats encountered, and its impacts do not resemble those of natural disasters. It is one of the reasons for demand shocks, impacts on the workforce, complications in the supply chain, and a world economic contraction. Due to sudden decline in total electricity demand and change in load pattern, power system operation is facing a higher degree of uncertainty. In traditional load curves, two peaks are prominent namely morning and evening peaks. But in the pandemic, the curve is much flatter. Indian grid operators adjusted different generation resources. The thermal generation has reduced by 29.21% whereas wind and hydro generation increased by about 26% and 4%, respectively. In long term, low demand may challenge power system security and financial stability for utilities in the future. Some of the aspects of power system operation affected by COVID are as follows:

4.1. Generation scheduling

Since a shortfall in demand has been observed, high-cost generators are put in standby mode to optimize the generation cost while meeting the demand requirements. Utilities need a new economic dispatch program to adjust and adapt to new curves accordingly [30]. As a consequence, system strength and damping capabilities are also reduced. Power sold back to the grid has been decreased which is the reason the curve is shifting upwards. This phenomenon is due to the stay-at-home policy which is encouraging prosumers to consume power generated at their end. Increasing renewable integration in the system is causing the duck curve to experience a lower back and a longer neck, as shown in Fig. 11. The difference in duck can be summed up as a 20% decrease in load curve and peak-to-valley difference is around 5% [31].

4.2. Voltage and frequency measures

Due to huge load reduction, the problem of voltage and frequency is occurring on the system on a wide scale. Maintaining the grid voltage and frequency during dynamically varied power demand and generation rescheduling is a difficult process. Voltage is a measure of the balance between MVar load and MVar capacity of the system. Frequency is the global parameter of the power system as well as the equilibrium point between demand (MW) and generation (MW) if losses are ignored. India experienced high voltage issues in the transmission grid during COVID, as shown in Fig. 12(a). The following measures are undertaken to cope with the voltage deviation problem [30]:

1. Reactors banks and synchronous generators are connected to the grid.
2. Unloaded power lines are disconnected without violating the security constraints.
3. Ancillary services are employed for voltage regulation support.

The problem of Under Frequency-based Load Shedding (UFLS) increased as a high reduction is seen in load in comparison with pre-COVID levels. Automatic UFLS has four stages of setting like...
49.2 Hz, 49.0 Hz, 48.8 Hz, and 48.9 Hz. This feature helps in avoiding cascading system disturbances, for example, generation loss or loss of in-feed on the system. The problem of backswing of frequency has also been witnessed in systems. Frequency Variation Index (FVI) occurred due to sharp reduction in load and scheduling of generation, as shown in Fig. 12(b) [30].

4.3 Ancillary service

Availability of frequency regulation ancillary service is dependent on generation technology and predicted demand of the system. If the current trend of work-from-home continues, there may be surplus generation as demand may be fulfilled by renewables. In such a scenario, conventional generators may be replaced and the inertia of the system would decrease. This will cause a deficiency of resources that can provide ancillary service. Therefore, a large frequency deviation even with a slight disturbance in the power system may be experienced.

4.4 Electricity markets

The implication of variable demand, changes in regulation and policies, disturbed electrical load composition and load profile shapes have a significant impact on electricity markets all over the world. Electricity prices have undergone a drastic decrease in India. Lower energy demand is also causing a drop in market clearing prices along with clearing volume [32]. Electricity markets are growing stronger for renewable due to looming uncertainty and viability of returns on the investment of conventional fuel technologies and oil prices in international markets. The real-time market is implemented on June 1, 2020, that accommodates the renewable variability by facilitating the trading near the delivery periods [33]. This will also reduce the requirement of reserve capacity to meet renewable variability in future and would bring required flexibility while ensuring optimal utilization of available surplus capacity.

5. System planning

With the reduction in electricity demand and its impact on system operations, it is important to look at their effects on power system planning to make it self-sufficient and immune to such changes. Ongoing pandemic is giving hard time to utilities. They have a balance between revenue shrink and the cost of maintaining the normal operation of the system. Lockdown and supply-chain restrictions are some of the reasons for delays in projects. About 3 GW of renewable projects are delayed in India alone amidst pandemic [34]. India is facing difficulties due to disrupted production and reeling under the shadow of the pandemic. Traditionally, conventional fuels were used for energy generation. Renewables are capturing a greater share in generation resources to achieve the twin aspects of the Paris Agreement and reducing carbon footprint. Different aspects in system planning being affected by pandemic are described as follows:

5.1 Fuel availability

Most of the developing countries are dependent on conventional resources that are either imported or exploited from the country’s reserve. Pandemic-related restrictions on imports have highlighted vulnerabilities associated with dependence on conventional resources-based generation. Thermal assets based on domestic coal of low calorific values lack power system flexibility which may be attributed to either technical or contractual limitations. Power sector decarbonization can be difficult as the
problem of low system flexibility can be a drawback for variable renewable energy penetration. Further, countries dependent on fossil fuels’ import in the region are prone to economic shocks and supply chain complications in the oil and gas commodity markets [35]. The global oil demand during the pandemic was at record lows to 29 mb/d, lower than the level seen in 1995, which is lower by 9.3 mb/d as compared to 2019 levels [36]. Restrictions on cross-border trading or other supply chain obstacles resulting in import restrictions though may be provisionally beneficial for electricity prices and IPP profit margins, but it may influence local price and availability, and may affect power sector operational integrity in long run.

Due to the above reasons, it can be seen renewables bucked the trend in pandemic time. Fossil fuel suffered the effect of reduced demand and coal was the hardest hit energy source.

5.2. Renewable energy transaction

As more renewables are being integrated into the sector, optimal pricing and generation of electricity will be achieved. It is pushing higher marginal costs power plants at low place merit-order. Though the global generation had decreased in the first quarter of 2020 by 2.6%, generation from renewable saw an increase in share from 26% to 28% [37]. It is creating a need to shift fossil fuel subsidies towards green energy. Reasons for such transition are as follows:

- Renewable Energy Generation: It has proved to be one of the most resilient generation sources as they have take-or-pay type PPA or feed-in tariffs. The global renewable generation has increased by 3% [37]. Since they incur no fuel costs, they are placed first in merit order dispatch. This has improved the carbon footprint of fuel.
- Supply Chain Disruptions: Since inter-border trading has been discontinued to contain spread of the virus, it has to extra incurred costs and delays in project completions. The COVID-19 has also highlighted supply chain susceptibility to future stocks.
- Demand for Legacy Fuels: Though Government policies and economic conditions are giving a push for energy transition but demand for conventional fuels will determine the success of the transition. This pandemic situation gave very little time for the procurement of fuels. So, it is an important time to think and relax dependency on imported fuels and reserves by diversifying the supply resources to avoid interrupted supply.

5.3. Infrastructure development

New wind and solar installations were supposed to come online by the end of the year 2020 as renewables experienced a growth in demand. However, new projects and ongoing projects are either being laid off or undergoing a delay process which is also a source of economic loss. Due to this, India is lagging behind its 2022 target for 175 GW renewable energy capacity by 93 GW [38].

6. Recommendations for future policies/plans

COVID-19 Pandemic being the highly rare event in history made such a large scale impact on the power system. COVID has exposed the weakness of the power sector and its ways of management of its services. The government intervened with various financial packages to save the utilities from going bankrupt. Power DISCOMs could write off pending dues of the generating company with help of a liquidity infusion of 900 Billion INR [39]. Some of the suggested reforms are: focus on transition towards renewable energy from fossil fuels, investment to upgrade the existing infrastructure, rapid digitalization of sectors and energy efficiency, etc [40]. Additionally, the following actions can be taken into consideration to avoid any kind of vulnerability and increase power system reliability during any similar events in the future:

6.1. Electricity distribution sector

Even in the COVID pandemic, the power sector is one of the sectors operating 24*7*365 to meet the demand of all. The sector is working continuously to accommodate the change in load pattern. Though there is a financial burden on the power system besides technical issues, the government intervened and ordered the utilities to avoid the disconnection of supply.

6.1.1. Demand side management

COVID-19 caused a great fall in overall demand, change in peak timings, an increase in residential load with a decrease in commercial and industrial demand [41]. However, many people have lost employment and are unable to pay bills on time. This necessitates the prompt implementation of demand-side management to retain the pre-pandemic shape of the load curve. The various mechanisms for demand side management can be adopted such as energy efficiency programs, and market-based and reliability-based demand response programs [42]. Market-based programs may include demand bidding and real time pricing. Reliability-based programs may include demand response via shiftable, curtailable and controllable loads. This will help consumers to reduce their energy costs by incorporating load shifting. In case of emergency, it can also prevent widespread power failure by carrying out controlled brownout [43]. Demand side management helps to reap economic, reliable as well as environmental advantages such as increasing the flexibility of power system, relieving transmission congestion, transmission and generation deferral, reduction in operating costs by efficient operation of thermal power units.

6.1.2. Energy efficiency measures

In pandemic times, energy efficiency can play an important role in providing security from economic shocks. Global energy efficiency is experiencing a downward trend and may further decrease due to COVID-19. Investment in global energy efficiency fell by 9% in 2020 [44]. COVID-19 has added uncertainty to energy efficiency measures due to the following reasons [45]:

1. Pandemic has caused an economic crisis which is one of the reasons for the delay in investment in efficient technologies.
2. Changes in customer behavior and markets are adding to uncertainty in energy efficiency progress.
3. Government policies are flag bearers of success or failure of energy efficiency technologies deployment.

At the same time, energy efficiency initiatives offer multiple co-benefits by creating energy cost savings, job opportunities and workforce development [46]. It can make a great impact on the way energy is being utilized nowadays.

6.1.3. Tariff restructuring

Utilities have experienced a revenue deficit in COVID-19 times due to a fall in electricity demand. Utilities are proposing the revised tariff to make up for revenue losses [47]. Rate cases are being suggested to address the immediate revenue shortfall and long-lasting impacts of crisis [48]. Instead of a hike in price to recover revenue loss, companies and utilities can reduce subsidies or discounts being offered to customers [49]. Reforms in tariff
structure are required in terms of reducing cross-subsidization in industrial demand.

Further, the implementation of real-time electricity pricing for large customers (entities with more than 1 MWh monthly consumption) can be a preliminary step in this direction. It is required to make it mandatory for DISCOMs to purchase all the electricity output from rooftop PV systems connected to the grid. These will act as a step towards achieving energy efficiency and conservation and will act as a driver in minimizing transmission losses, distribution losses and overall cost of electricity [50].

6.2. System operations

Harmonized system operation is possible by incorporating the experiences of past events and anticipated future challenges. For smooth system operation, the following sections need consideration:

6.2.1. Flexibility enhancement

COVID-19 pandemic highlighted the need for flexibility enhancement to make the grid more resilient. The pandemic has acted as a catalyst for the enhancement of system flexibility and integration of energy storage which have been underway for the smooth integration of renewable energy sources, as a similar scenario of demand variation and replacement of conventional resources with renewables has been anticipated. The lights-off event is successfully managed owing to flexible resources in the grid. 10 MW support was provided by Delhi Battery Energy Storage System (BESS) to balance out the demand drop as the event began [51]. The event gave an opportunity to examine system flexibility adequacy for a similar situation when a sudden change in generation can happen due to a high share of variable renewable energy sources.

Flexible generation is needed to counteract the gap between the peak and lean hours [52]. As renewable penetration accelerates to meet the target of 450 GW by 2030, the need for flexibility intensifies [53]. The flexibility can be harnessed from all available resources such as fast-acting gas power plants, variable renewables themselves, energy storage, demand response and grid interconnection, though adequate market reforms are required that can ensure efficient utilization of heterogeneous resources having divergent costs. BESS when used in conjunction with demand response, increases the stability of grid manifold times. Utilization of energy storage and efficacy of demand response in providing flexibility can be further enhanced by integrating Dynamic Thermal Rating (DTR) technologies that help to penetrate more renewable energy into the system by relieving transmission congestion. A case study demonstrates that the combined use of these three technologies reduces curtailment and system dispatch costs as compared to their use in isolation [54]. DTR system helps to enhance the ratings of overhead transmission lines by providing their actual current-carrying capacity based on real-time operating conditions [55]. This reduces renewable curtailment caused due to transmission congestion and hence reduces load curtailment acting as demand response to maintain the grid security.

6.2.2. Market reforms

With the total installed capacity of 369 GW against the peak electricity demand of 183.8 GW, India is having surplus generation availability. However, almost 80% capacity is under long-term PPAs. This causes long-term PPAs to exceed peak demand in some states. In India, utilities have no rights to trade the contractual capacities. Also, there is no provision to revise the contracts according to future contingencies such as sudden reduction in electricity demand during pandemic. So there is a need to have some kind of flexibility elements in long-term PPAs or provision to renegotiate/review the terms and conditions or exit the contract in 7–8 yrs (mid period of their contractual life when they complete the pay back period) to address unforeseen situations. This would help to remove the conflicts between future availability of low cost supplies and high cost existing contracts. This will further mobilize investors’ interest and benefit the end use customers.

Though India has achieved open access in transmission and distribution, competitive supply is limited due to scarcity of available transmission capacity and incompetent market structure. This led generation to locked in at regional and state levels. Experience from European Union and United States can assist to reduce the state level dominance by increasing trading between different regional grids of India. A country-wide wholesale electricity market with common rules for transmission and dispatch across different regions would increase reliability and cost-effectiveness by increasing the DISCOMs’ operational flexibility.

6.2.3. Improved forecasting

Coronavirus pandemic has affected and altered the load shapes all over the world. All load forecasting models are generally trained on historical data and follows the underlying assumption that the energy consumption pattern will remain the same. However, these models failed to produce forecast results with the desired level of accuracy for pandemic period [56]. Identified reasons for accuracy failures are poor data input, wrong modeling assumptions, high sensitivity of estimates, lack of incorporation of epidemiological features, poor past evidence on effects of available interventions, lack of transparency, errors and lack of determinacy [57]. PAN India light off event highlighted the importance of another factor i.e., consumer behavior in load forecasting. Forecast accuracy for such rare events where a response to non-economic signals is desired could be improved by the integration of consumer behavior in forecasting techniques.

Pandemic was an aperiodic event but its impact on the power system was long-lasting. Traditional forecasting models are not able to retain the memory of rare events which brings down the forecasting efficiency. Long–Short-Term-Memory (LSTM) method overcomes the above said problem [58]. The LSTM method can further be improved by incorporating energy consumption behavior features in the load forecasting model. The major impact of the lockdown was caused by the absence of people from work places which resembles the situation on weekends. During this situation, population-level mobility data such as traveling and shopping trends demonstrate the changing pattern of consumer behavior. A study introduces the concept of mobility data as an economic activity measure to improve the electric load forecasting during pandemic situations [59]. The study highlights that mobility is highly correlated with regional economic activities. In this study, the baseline case, i.e., without incorporating mobility data gives Mean Absolute Percentage Error (MAPE) of approx. 10%. The forecasting results have been improved by 3.98 times by incorporating mobility data. Further, as the data for such rare events where consumption of different customer types does not follow a systematic pattern is sparse, techniques such as transfer learning and clustering are more effective [60].

6.3. System planning

System planning is a crucial aspect of maintaining the integrity of the system. It plays an important role in determining the system’s robustness and reliability. Following are the recommendations in this area:
6.3.1. Fuel security and alternative technologies

Pandemic highlighted the vulnerabilities related to dependence on conventional and imported fuels. India needs to diversify its resources. Besides renewable resources, nuclear and large hydro have a great scope in India. Natural deposits of Uranium and thorium amount to be around 70,000 tonnes and 3,60,000 tonnes, respectively [61,62]. Both have good potential to be utilized as fuel in nuclear reactors in India.

6.3.2. Network reinforcement

Since many operations have shifted to remote-working due to an ongoing pandemic, secure network connections are needed even for the residential sector. Third-party access to plant production and grid networks must be avoided, as this increases the risk of outages and network attacks. The maintenance of the system is generally well-scheduled in advance to avoid disruption of load during the process. It ensures system reliability. But ongoing pandemic has either canceled or postponed such works. Technologies like AI-aided dispatch systems, planning, and operation strategy for systems with high resilience, and no operator substation were adopted for power system management during the pandemic. Technologies such as DTR can also assist to maximize the utilization of existing networks by considering actual weather conditions. In addition, DTR enhances the ratings of overhead lines to mitigate network congestion and relieve power flow bottlenecks. Furthermore, it has potential to improve wind penetration in system [54].

6.4. Required immediate measures

Different regulatory reforms have been carried out to save the power system utilities from the vicious cycle of impacts of the COVID pandemic. Some immediate actions that can be taken for the benefit of consumers are [63]:

1. Government must identify the domestic electricity distribution sector as an emergency sector and staff should be provided with all protection facilities.
2. Residential, commercial and all other essential and emergency services should get an uninterrupted and reliable supply of electricity indiscriminately.
3. There should be at least a minimum of 15% discount to all domestic and residential energy users in electricity bills to provide financial relief to residents.
4. 100% discount in electricity bills for at least lockdown period should be provided to the commercial sector that has incurred a loss of business and revenue in COVID-19 lockdown.
5. Until pandemic exists, at least for a period, utility bill payments should not be penalized.
6. Electricity distribution companies and their employees should be provided with incentives by the government to boost the morale of employees and as recognition for their dedicated work of providing uninterrupted energy during COVID-19 emergency.

7. Conclusions

COVID-19 being a health-related pandemic has affected all spheres of life, including the power sector. Measures like lockdown and stay-at-home policy have resulted in a decrease in industrial and commercial sector demand but residential demand increased manifold times. Due to changes in lifestyle and habits, a shift in morning and evening peaks is observed. As different levels of restrictions are implemented, the load profile changed. Reduction in demand of Indian power systems has been discussed and analyzed following the lockdown measures, and the consequent impacts on operation and planning strategies of the power sector.

It is shown that energy consumption plummeted suddenly in March 2020 due to country-wide lockdown and again started recovering from the end of April 2020. Utilities are taking steps to tackle challenges arising from load changes for smooth operation and maintenance of the power system. It has been observed that a large amount of renewable capacity was facing payment dues during the lockdown period with the highest 50% of installed capacity observed in Tamil Nadu state. Various options such as rate case, removal of subsidies and tariff revisions have been suggested in the manuscript as immediate and long-term actions to make up revenue losses.

The Covid scenario has provided an experience of a high renewable scenario. During this period, many thermal generators were either in a shutdown state or were operating near to minimum stable generation. However, the system was having sufficient flexibility to meet renewable variability. This exhibits the requirement of flexibility enhancement for future low-carbon power systems when the conventional power plants will be displaced by variable renewables. Further, the nine-minute light switch-off event on April 5, 2020 highlighted the need for new forecasting techniques for electricity demand that can capture the consumer response for non-economic signals.

The study has also examined various issues faced by the utilities in maintaining grid frequency and voltage profile within their recommended band. It is observed that the Indian utility managed to supply uninterrupted power to all, including under extreme conditions like light switch-off event. A need of ensuring energy security is also highlighted as restrictions on imports during any such future events may expose the country to an energy crisis.

Moreover, grid operation digitization, adoption of energy efficiency measures and advanced metering can provide value chain support. There is an immediate need to revise the existing policies, adaptation from international business practice and innovations of break-through/cutting-edge technologies to make the system long-term resilient and cost-efficient to handle the crisis during such pandemic. The overall review and investigations performed, and recommendations presented in the paper will be useful for utilities and policymakers to handle any such scenarios in the future and to devise new policies for sustainable growth of the power sector globally.

CRediT authorship contribution statement

Shivanjali Yadav: Conceptualization, Writing – original draft, Visualization, Investigation, Formal analysis, Writing – review & editing. Anjali Jain: Conceptualization, Writing – original draft, Visualization, Investigation, Formal analysis, Writing – review & editing. Rohit Bhakar: Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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