Applied Energy 279 (2020) 115739

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

COVID-19: Impact analysis and recommendations for power sector operation

Rajvikram Madurai Elavarasan [a,*], GM Shafiullah [b,*], Kannadasan Raju [c], Vijay Mudgal [d], M. T. Arif [e], Taskin Jamal [f], Senthilkumar Subramanian [g,h], V.S. Sriraja Balaguru [i,h], K.S. Reddy [d], Umashankar Subramaniam [j]

[a] Electrical and Automotive Parts Manufacturing Unit, AA Industries, Chennai 600123, India
[b] Discipline of Engineering and Energy, Murdoch University, Perth, WA 6150, Australia
[c] Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering, Chennai 602117, India
[d] Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[e] School of Engineering, Deakin University, Waurn Ponds, Geelong, VIC 3216, Australia
[f] Department of Electrical and Electronic Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh
[g] State Load Despatch Centre, Grid Operation, TANTRANSCO, Chennai 600002, India
[h] Department of Electrical and Electronics Engineering, College of Engineering, Anna University, Chennai 600025, India
[i] Non Conventional Energy Sources, TANGEDCO, Chennai 600002, India
[j] Department of Communications and Networks, Renewable Energy Laboratory, College of Engineering, Prince Sultan University, Riyadh 12435, Saudi Arabia

HIGHLIGHTS

- Investigation on potential impacts in power sector due to COVID-19 pandemic.
- An analysis on Indian power system scenario during pandemic is presented.
- Measures to combat unforeseen reduction and shifting of electricity demand.
- Recommendations are provided for risk management in power and energy sector.

ARTICLE INFO

Keywords:
COVID-19
Power systems
Load demand
Global power systems
Indian power system
Recommendations for sustainable power systems

ABSTRACT

The demand of electricity has been reduced significantly due to the recent COVID-19 pandemic. Governments around the world were compelled to reduce the business activity in response to minimize the threat of coronavirus. This ongoing situation due to COVID-19 has changed the lifestyle globally as people are mostly staying home and working from home if possible. Hence, there is a significant increase in residential load demand while there is a substantial decrease in commercial and industrial loads. This devastating situation creates new challenges in the technical and financial activities of the power sector and hence most of the utilities around the world initiated a disaster management plan to tackle this ongoing challenges/threats. Therefore, this study aims to investigate the global scenarios of power systems during COVID-19 along with the socio-economic and technical issues faced by the utilities. Then, this study

Abbreviations: ACT, Actual; CEEW, Council of Energy Environment and Water; CERC, Central Electricity Regulatory Commission; DISCOMs, Distribution Companies; DSM, Deviation Settlement Mechanism; ER, Eastern Region; ERLDC, Eastern Regional Load Dispatch Centre; FY, Financial Year; FVI, Frequency Variation Index; IEGC, Indian Electricity Grid Code; IEX, Indian Energy Exchange; IISD, Institute for Sustainable Development; IR, Indian Rupee; MCP, Market Clearing Price; MCV, Market Clearing Volume; NER, North Eastern Region; NERLDC, North Eastern Regional Load Dispatch Centre; NHPC, National Hydroelectric Power Corporation; NLDC, National Load Dispatch Centre; NR, Northern Region; NRLDC, Northern Regional Load Dispatch Centre; NTPC, National Thermal Power Corporation; NREL, National Renewable Energy Laboratory; PGCIL, Power Grid Corporation of India Ltd; POSOCO, Power System Operation Corporation; PXI, Power Energy Exchange; RES, Renewable Energy sources; RLDC, Regional Load Dispatch Centre; SCH, Schedule; SLDC, State Load Dispatch Centre; SR, Southern Region; SRLDC, Southern Regional Load Dispatch Centre; STATCOM, Static Var Compensator; UFLS, Under Frequency based Load Shedding; USAID, United States Agency for International Development; WR, Western Region; WRLDC, Western Regional Load Dispatch Centre; VAR, Volt Ampere Reactive; VDI, Voltage Deviation Index.

* Corresponding authors.
E-mail addresses: rajvikram787@gmail.com (R. Madurai Elavarasan), GM.Shafiullah@murdoch.edu.au (G. Shafiullah), kannan.3333@yahoo.co.in (K. Raju), er.vijaymudgal@gmail.com (V. Mudgal), m.arif@deakin.edu.au (M.T. Arif), taskinjamal@gmail.com (T. Jamal), sendilkumar26@gmail.com (S. Subramanian), srirajabalaguru@gmail.com (V.S. Sriraja Balaguru), ksreddy@iitm.ac.in (K.S. Reddy), usubramaniam@psu.edu.sa (U. Subramaniam).

https://doi.org/10.1016/j.apenergy.2020.115739
Received 8 May 2020; Received in revised form 1 August 2020; Accepted 18 August 2020
Available online 31 August 2020
0306-2619/

further scrutinized the Indian power system as a case study and explored scenarios, issues and challenges currently being faced to manage the consumer load demand, including the actions taken by the utilities/power sector for the smooth operation of the power system. Finally, a set of recommendations are presented to support the government/policymakers/utilities around the world not only to overcome the current crisis but also to overcome future unforeseeable pandemic alike scenario.

1. Introduction

The driving force of the economy is energy. Energy, economy, business, development and growth all are primarily dependent on public demand, capacity and affordability. Public health and safety are the primary variances to maintain the demand as well as growth. The growth and development were interrupted many times due to disease outbreak such as; Circa of China in 3000BCE, Plague of Athens in 430BCE to the last recent Zika Virus epidemic in 2015 [1] and all these causes thousands of deaths. The first quarter of the year 2020 is inexplicable to observe global lockdown due to a new virus outbreak. WHO (World Health Organization) declared it as pandemic on March 12th, 2020 [2]. This disease is spreading throughout the world and the most affected countries include mainland China, Iran, Italy, Spain, France, Germany, the UK and the United States. The United States of America (USA) alone experienced 68,797 deaths as of 4th May 2020 due to COVID-19 [3,4].

As there is no medicine yet, therefore maintaining the social distancing is the best approach to minimize the spreading and most of the countries imposed nation/state wise strict lockdown [5–7]. The lockdown, social restriction, travel ban, unemployment and working from home policy forced most of the people to stay inside the house, which affected the normal business operation and reduced energy demand from the national grid. Industries moved to the minimum manual operation or limited their operation. Business reduced their operation; travel ban almost collapse the aviation industry, small business almost stopped, schools, universities moved to online mode and most other sectors adopted working from home policy.

The global economy is affected greatly due to these activities and increases unemployment and poverty. These brings threats in achieving the UN mission of Sustainable Developments Goals (SDGs). More visibly, this pandemic event has impacted the social and economic areas of a country [8–11] at least in the following areas:

- Industrial operation and business slow down and the global stock market crashed by more than 25% in March 2020 [12] and ongoing lockdown can lead to a global economic recession. It is estimated that the COVID-19 outbreak will cost around $1 trillion to the world's economy in 2020 [13].
- The international oil price has dropped in March 2020 to the lowest level since 2003 due to the combined effect of COVID-19 related demand drop and business issues among Saudi Arabia, USA and Russia [14].
- Due to the closure of educational institutes worldwide, more than 91% of the registered student has been affected [15]. However, several schools, colleges and universities have shifted to online classes to continue education which also effected the power systems.
- Most of the governments and organizations around the world are putting efforts and money to fight against COVID, hence, there is a possibility of delay or reduction in funding of several research activities such as renewable energy projects or initiatives. On the other hand, this pandemic has brought forward few multidisciplinary research scopes like research in complex medical emergency management [16–18], mental healthcare [19,20], economic revival, power sector management to better manage power system in such critical conditions [21–23], etc.
- Due to COVID-19 transportation sector is seriously affected and the most affected part of it is the aviation industry. As the aviation sector is completely in standstill, the related service in all airports is also stopped which impacted a huge drop in electricity demand.
- The use of public transport has been dropped as much as 80% to 90% in major cities in China, Iran and U.S.A. and depending on city/route as much as 70% for some operations in UK [24]. Although all modes of public transports are not electrical, however in many countries a significant part of public transport are electrical such as; tram, train and public vehicles are electrical and less traffic impacted the electricity demand in transportation sector too.
- The strict lockdown has halted the industrial operation, due to a lack of manpower and restricted business due to a travel ban as well. All these have indirectly helped in emission reduction from the industry sector, which is a positive effect on the environment. Satellite images from the European Space Agency show the drop in Nitrogen dioxide (NO_2) level in the lower atmosphere during the lockdown period. Fig. 1 (a) shows a substantial reduction in emission in major European cities such as; Paris, Milan and Madrid during the lockdown period in 2020 compared to the same time emission in 2019. Similarly, Fig. 1(b) shows the emission reduction across India's industrial hubs during the lockdown period.

Sudden change in lifestyle has dramatically increased the residential electricity demand and reduced electricity demand in business and industry and that eventually affects the national energy demand profile. This may adversely affect the network equipment such as a substation, distribution transformers and protection equipment. In India, 10 min nationwide light off event was observed to mark the people's participation in national lockdown. This could have a serious impact on the national grid if it was not managed properly by the utility. Currently, the outbreak is in peak condition in most affected countries and there is no clear idea when it will end; moreover, it is moving to new regions/countries such as in Africa, Latin America and Middle-East. It is predicted that a similar impact may hit all countries. Governments along with power industries should take precautionary measures so that they can tackle the issues and challenges observed for the smooth operation as well as reshape the energy sector for the future that can overcome future unforeseeable pandemic alike scenarios. Therefore, this paper has investigated the impact on the electrical power system due to the lockdown or social distancing measures taken to reduce the spread of COVID-19 as well as discusses possible measures to improve the performance of the power and energy sector and grid operation under such conditions in the future.

2. Methodology

The proposed study aims to analyze the impact on energy and power sector with the prospective recommendations to encounter the impacts during COVID scenario and also, in future. To explore and analyze the impacts caused by the pandemic, it demands piles of data accompanied by tremendous efforts to identify the issues in the power sector in all aspects. Fig. 2 represents the research framework of this study. This study initially focuses on the menaces created in the energy sector that occurred at a global level, and it can be categorized as direct and indirect impacts. Direct impact indicates the changes that happened in the grid system during the pandemic such as power demand variation and the subsequent effect on energy cost, while the indirect impact details the consequences of the pandemic that revolves around the parameters which ultimately enhances the energy sector operation such as the implementation of new projects, investments etc. A data-driven analysis is accomplished for investigating the direct impacts on the global scenario where the data (e.g. demand load data, power generation data) is obtained either from the trusted website (open access data) of country's or regional energy sector or through requesting them the requisite data (if not open access) for this study. Authors succeeded in collecting four country's meticulous power system data, dated within the pandemic period (that includes USA, Italy, Australia and India). While surface-level data is obtained for countries like France, Italy, Spain, Portugal, Belgium, Netherlands, Germany, UK, China and Singapore which are grouped as other countries and the impact is quantified in terms of power demand variation. Considering the indirect impacts, the impact information is retrieved by extensively surveying the journal articles (Scopus indexed) as well as by scrutinizing the information obtained from the reputed online platforms such as IEA, IRENA, BBC and World Economic Forum. In a similar way, the authors have investigated the measures implemented by the various governments or authorities across the globe for tackling the impact and framed the same under Table 1.

Further, we have decided to step up the investigation of the pandemic impact on the power and energy sector by at least focusing deep down into any one of the countries. Since the authors felt that India is a potential candidate for such analysis and also, various reasons were supporting the claim such as third-largest energy consumer, increased focus towards renewable energy, a wide range of culture, significant population and many others. Regarding the investigation methodology, an in-depth discussion was first carried out among the authors, the utility workers and authorities to figure out the potential issues and emerged practical issues that occurred during the pandemic. The team of authors is framed in such a way that they are composed of technical experts in power systems and utility authorities who had ultimately helped in providing the foundation data that required to build the case study. From which, the real-time data is obtained, and the subsequent investigation of a solution is carried out in context with various power system characteristics as categorized under Section 4. Another unique event that occurred in India is the light-off event which is carried out as a token of appreciation to the healthcare workers. The possible impacts behind such an event are brought under the light by the authors and the real-time solution that the utility workers adopted in tackling such issues are presented here precisely. Along with this, the socio-economic issues, technical issues and the challenges are briefly discussed.

Finally, the recommendations to overcome the impacts that prevail in the power and energy sector is detailed in Section 6. The recommendations are well-established through the joint-efforts of technical experts and utility authorities such that the solutions are more pragmatic, which can be easily adopted. Furthermore, the recommendations during COVID are concentrated to emphasize safety, frame technical strategies, enhance consumer interaction, strong financial plan, and to recommend from a governmental point of view in terms of policies. To provide a direction for sustainable energy sector, suggestions are provided from energy generation, transmission, consumption aspects, and to promote digitalization, impart resilience, and also, for improving efficiency and flexibility of the grid system. Section 6 successfully attempted to clarify the research question – "*how the post-COVID-19 power and energy sector should be designed and look like, incorporating the lessons learnt during this period and implementing these in a redesigned power system*".

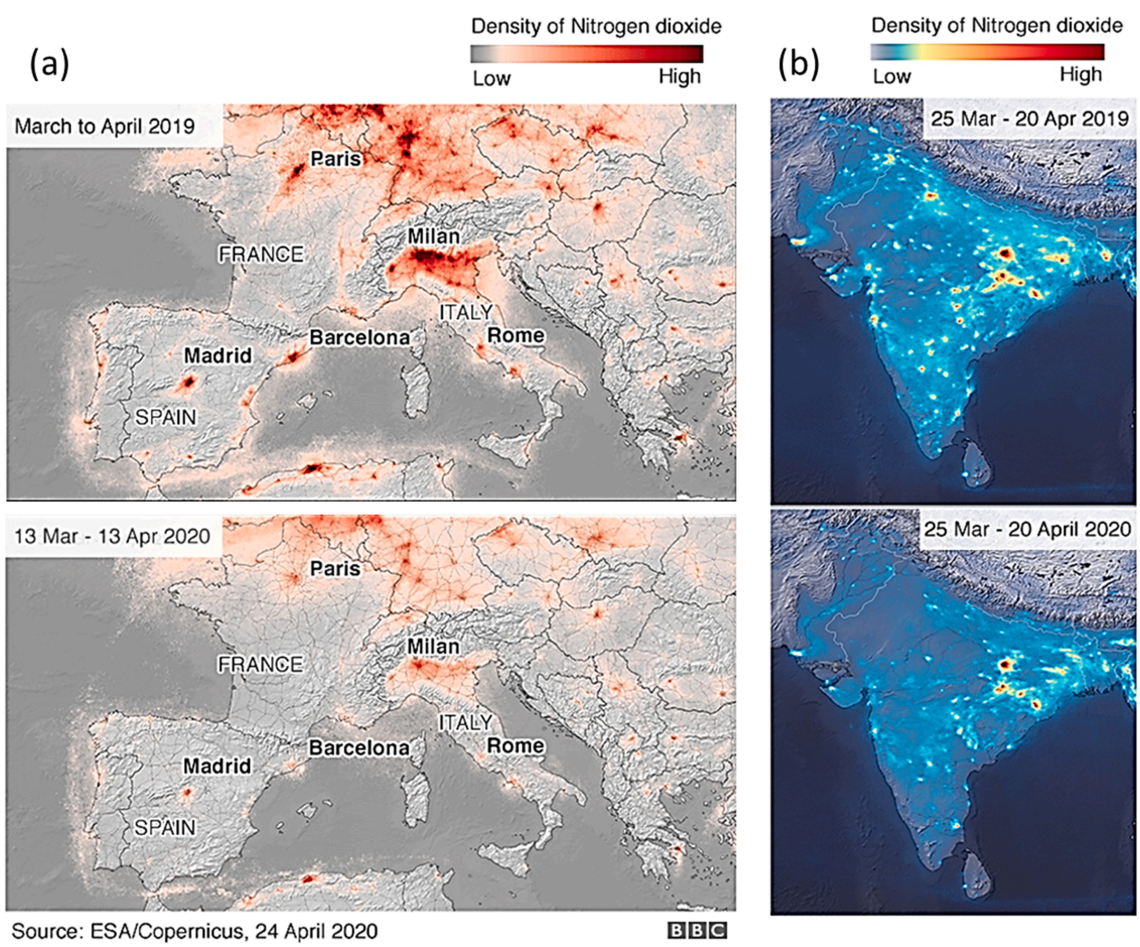

Fig. 1. Change in NO_2 emission level in atmosphere (a) European skies and (b) Indian skies [25].

3. Impacts on power systems- A global scenario

3.1. Direct impacts

Direct impacts emphasise the impact or the change that occurred on the existing working systems owing to the effects of pandemic. Such impact includes fluctuations in the power demand across all the COVID affected regions and also, the resulted effect in energy cost.

3.1.1. Power demand variations

Overall, the power systems load can be classified mainly as residential, commercial and industrial types. These types of loads have a typical load pattern and utility operators manage the generation accordingly. However, transportation and agriculture load have also become a significant load for the power grid. During the COVID-19 outbreak, the percentage demand of electricity for these sectors has been changed and therefore, the new load mix in different countries has observed. Fig. 3 shows the distribution of different types of loads in the USA, Italy, Australia and India in Pre-Covid (PC) and During COVID (DC) periods [26].

New York, USA:

New York City (NYC) is the most affected city in the USA as well as in the world due to COVID-19. The daily average load demand from January to April in 2020 and 2019 clearly shows a significant drop in demand, particularly in March and April 2020 compared to 2019 demand, as can be seen in Fig. 4. It was found that daily electrical energy demand or total daily consumption dropped 2.9% in February to 13.7% in April compared to the same time in 2019 [28].

Italy:

When full lockdown applied in Italy, the grid power demand also dropped, as can be seen from in the figure the comparison of load demand for the same period in 2019. It was observed that the peak load demand drops around 3–4% when partial lockdown applied as people are trying to adjust with the changes, however peak demand, as well as daily total energy demand, drops 6–10% in Weekend and 18–22% in weekdays when full lockdown applied as shown in Fig. 5 [26].

Australia:

Australia is one of the leading countries which is performing better to control the spreading of COVID-19 by applying strict nationwide lockdown. Like many other countries, spreading accelerated in early March 2020 and reached a peak in the last week of March and gradually dropped to the lowest level in the last week of April 2020.

From 6,731 confirmed cases in Australia, over 3,000 cases are in New South Wales (NSW) and lockdown restriction also affected power demand more in this state. Fig. 6 (a) shows daily load profile from January to April in 2020 compared to the same in 2019 and it is found that during March, the highest load reduction occurred, around 7.15%, followed by April of 5.65% compared to the same time demand in 2019 [29].

The peak load demand in NSW decreased by 3%, 6.7% 5.2% for February, March and April respectively in 2020 compared to the same time in 2019. Similarly, peak load demand decreased in other Australian states as shown in Fig. 6 (b).

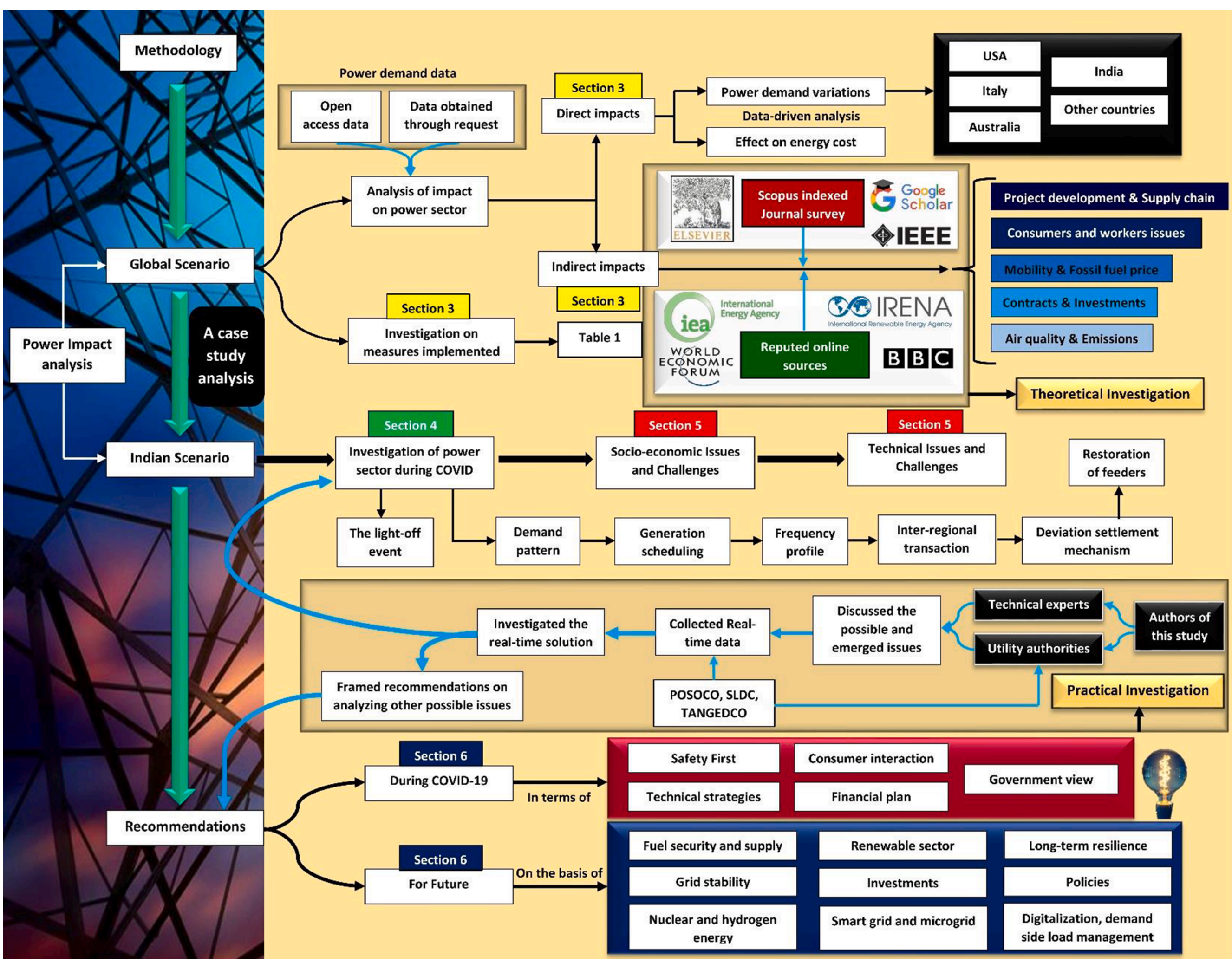

Fig. 2. Research framework of this study.

Due to COVID-19, the downturn economy will inevitably have an impact on energy systems. In Australia, the overall electricity demand was down by 6.7% in March. Comparing the pre-lockdown (1 – 7 March) and post-lockdown (22nd – 28th March) data in one substation in North-Western Melbourne under similar weather condition shows, decrease in commercial demand by 7% (which usually accounts for the highest usage), decrease in industrial demand by 1% and increase in residential demand by 14%, however overall demand for the week in lockdown increased by 1% [30].

This change in demand by different types of load is summarized in Fig. 7. It was observed in Australia that, although there is a dramatic shift in energy demand across different sectors, however, overall demand has not dropped significantly compared to other countries like USA, Italy and Spain.

India:

In India, lockdown started from March 25th, 2020, and the electricity Market Clearing Volume (MCV) immediately as wellolume as the Market Clearing Price (MCP) also dropped, as can be seen from the Fig. 8. As per economy, price of a product is set at a point where demand is equal to the supply. Similarly, electricity Market Clearing Price (MCP) is the lowest price at the point of intersection of aggregated supply and demand curves. The average MCP for March and April 2020 was IR2456/MWh and IR2448/MWh, respectively, however, it was IR3118/MWh in March 2019 and IR3221/MWh in April 2019 respectively [31].

Other countries:

As we have seen, the COVID-19 has an impact on electricity demand and the demand for electricity in most European countries has reduced, especially in a country like France, Italy and Spain where the spread of the virus is severe. The decline in electric demand in France, Italy, Spain, Portugal, Belgium, Netherlands, Germany and UK are 14.8%, 11%, 7.1%, 6.4%, 6.1%, 5%, 4.9% and 6% respectively as shown in Fig. 9(a). Energy demand reduction in some other major countries like the USA, India, Singapore, Australia and China are 5.7%, 26%, 8%, 6.7% and 7.8% respectively, as shown in Fig. 9(b).

3.1.2. Effect on energy cost

Due to decreased electricity demand, energy prices declined in most European markets. The energy price in the third week of March 2020 decreased compared to the second week of March 2020, as shown in Fig. 10 [34]. European power exchange (EPEX SPOT) market price of Belgium (BE), France (FR) and the Netherlands (NL) decreased by 23%, 20.1% and 18.2% respectively [38]. Similarly, the Italian Power Exchange (IPEX IT PUN), MIBL market in Spain (ES) and Portugal (PT) decreased by 17.7% and 17.4% respectively [39]. However in Germany (DE) and UK, change of overall energy demand remains positive as the lockdown in those two countries started from 20th and 24th March 2020 respectively. It is to be noted that the increase in price was less than 1.8% in the German market for the mentioned week with several hours of negative pricing averaging of €0.95/MWh. In the British market, the increase in price was less than 2.8% for the mentioned third week of March. With further continuation of the lockdown, the electricity demand and the electricity price at different European exchanges declined [34].

As evidenced in Fig. 3 and subsequent discussions, it was observed that the electricity demand has dropped for commercial and industrial loads but increased for the residential load for most of the studied countries as the industrial and commercial activities were restricted while people imposed to stay at home and working from home. This has changed the load pattern for network infrastructure and the energy price also dropped as a consequence. Due to significant changes in energy demand, operation of the power system has become critical and to handle the situation, government needs to offer an exigency or emergency plan for users as well as for utility operators. This study highlighted the current measures taken as well as the future intiatives need to be undertaken to address the impacts of COVID-19.

3.2. Indirect impacts

Indirect impacts mark the menaces created on some parameters that ultimately supports the power and energy sector in numerous ways such as new projects, investments and consumer relations. Impact on such parameters though does not affect the current power system functioning, but it would have a prolonged effect on the development of the power systems. Hence, this section elucidates various indirect impacts that reflected in the power and energy sector owning to the pandemic.

Due to COVID-19, energy demand has decreased in the industrial and commercial regions; however, increased in the residential areas. Overall, almost every region hit by the event has experienced a reduction of overall electricity demand by around 10–30%. The centralised fossil fuel-based power generation has decreased due to lower demand. However, due to national policies, renewable energy penetration level into the grid increased and this posed both positive and negative issues [40]. The report published by AEMO also discussed the same issues of electricity demand change for Australia [41]. The US congress website also portrayed a similar observation in the United States [42]. The Department of Industry, Science, Energy and Resources of the Australia Government have published their responses regarding the energy sector operation in Australia. They have discussed their current cooperative role with other governmental agencies and the energy market operators. The customer connection-disconnection issues and associated financial issues were also well clarified in this response [43].

An International Energy Association (IEA) report and an IEEE Power and Energy Society report discussed the recent issues of health and economic crisis around the world due to the pandemic event. The reports also investigated the issues of decline in demand for mobility and lockdown impacts on current demand, supply chain disruptions, impact on energy consumption and peak demand, and mid- to long-term impacts. The management of the control centre and field operations, handling the customer operation, mitigating the technical issues, regional impacts & mitigation measures and future investment in the electricity sector were also discussed in these reports [44]. Dr. Fatih Birol, Executive Director of the IEA, mentioned in his article that, "*The coronavirus crisis reminds us that electricity is more indispensable than ever*". He also discussed the flexibility of the sector, building cyber defences and emphasized on building a secured and sustainable future [45].

International Renewable Energy Agency (IRENA) and the Council of European Energy Regulators (CEER) discussed issues including the importance of fuel diversification, integration and sustainability of energy production, positive effect on climate goals, the conversion of the energy system towards a "clean energy system", solar and wind power becoming competitive, renewable power investment opportunities and a shift to clean hydrogen [46].

A report from United States Agency for International Development (USAID) and National Renewable Energy Laboratory (NREL) focused on the impact on the power sector in the region of Southeast Asia. It discussed the issues of impacts and opportunities on power demand, energy efficiency, utility modernization, sector reform, subsidy reform etc. in this region. Additionally, the report discussed in detail about the contracts and investments, air quality and emissions, energy sector workforce, clean energy transition (renewable energy generation, project development, supply chain disruption, fossil fuel price, public sentiment, business planning and clean energy for economic recovery). The report also emphasized on the issues of long-term energy sector resiliency through proper planning of power sector, critical services and financial matters [47].

The "pv magazine" have discussed the COVID impacts and the post-COVID policies and the to-dos. They reviewed the construction of new energy facilities and infrastructure delayed or stopped, a default of payment due to COVID-19 and further discussed the responses of policymakers, regulators, and market participants [48]. IRENA also recommended about the post-COVID energy sector formation. The issues discussed broadly were meeting the medium- and long-term development and climate objectives, stimulus and recovery packages, energy transitions, decentralised solutions, recovery measures, research and innovation, policymakers' role and international co-operation in the field of energy [49]. The issues highly focused in the IRENA Coalition for Action report were regarding the revisiting of the deadlines for renewable energy projects that faced contractual obligations for near-term delivery, designating the renewable energy industry and related infrastructure as a critical and essential sector, affirming and extending policies promoting renewable energy solutions-both centralised and decentralised, prioritising the renewable energy sector by stimulus measures, commit to phasing out support for fossil fuels and providing public financial support to safeguard the industry and mobilise private investment in renewable energy. The report also discussed the issues of enhancing the role of renewable energy in industrial policies and strengthening international co-operation and action to accelerate renewable energy deployment in line with global climate and sustainability objectives [50]. The IEA Statistics Report, dated May 2020 also discussed the impact and strength of the renewable energy sector for the post-COVID era [51].

A report published by the Union of the Electricity Industry - Eurelectric aisbl conveyed a few recommendations on electrification and sustainability, generation and environment, markets and investments, distribution and market facilitation, customers and retail services regarding the COVID impacts [52]. Digitalisation of the power and energy sector is one of the strong recommendations to battle the vulnerabilities of the sector that has been exposed. This fact is also strongly mentioned and raised by the World Economic Forum [53]. A report in the "microgridknowledge" stated that building microgrids would pose a progressive impact on rebuilding the economy and also tackling the power and energy sector challenges [54]. Developing a microgrid-based power system facilitates smart controls, integration of clean energy and ability to support the grid during any crisis. Community microgrids which are capable of providing critical services are very much compatible with addressing many challenges stimulated by a pandemic event.

The nuclear power industry would attract more employments to boost up the economy if more large-scale nuclear power plants are planned to be built in future as mentioned in BBC New. The World Nuclear Association also projects that nuclear power plant uptake will increase in future [40]. The transportation sector can be highly decarbonised using hydrogen as an alternative fuel. In the wake of the Covid-19 crisis, the EU and Germany have indicated their interest in investing in this sector [40].

To summarise, the impacts due to the pandemic has posed various challenges and consequentially opened the doors for new opportunities and improvements in the power and energy sector. All international organizations and government agencies acknowledged that the utilities had been challenged to overcome the new normal scenarios. Though no severe issues have been reported by utilities during the pandemic period, yet they have been preparing to combat against any unforeseen threats. Utilities are also investing now on improved system flexibilities to tackle the technical issues due to load reduction and shifting of daily peak demand. A necessity for system digitalization is another issue which many utilities have addressed. Recovering economic losses incurred by the sector entities would be tricky. During the lockdown period, high renewable penetration into the distribution network has also caused several technical and economic challenges. The stakeholders associated with policymaking have been observing all these issues for adopting new policies for the post-pandemic period to continue supporting the sustainable growth in the sector, which consists of integrating next-generation technologies championed by zero carbon emission mechanisms. These recently published research papers, news articles and media coverages form the fundamental basis to formulate the recommendations to address during COVID and post COVID direct and indirect impacts to build a sustainable power system for the future.

3.3. Implementation measures

Though the impacts prevail in various forms in energy and power sector, some of the measures that are implemented by the government bodies or the concerned authorities of the respective sectors in different couries are summarized in the Table 1.

Thus from the above analyses, it can be summarized that the following scenarios have occurred due to the COVID-19 outbreak:

- Commercial load demand dropped the maximum.
- Residential load demand increased.
- Industrial load demand also dropped but not very significant in many countries.
- Energy demand price dropped in most of the countries.

Although this section scrutinizes the impacts of COVID for different countries from the available data, it is an essential task to explore any of the discussed countries in detail to divulge the concrete impacts of COVID in the power sector. On that note, the Indian grid is considered as a case study for further deliberations as given in Section 4. It has been selected based on several factors as given below:

- Third largest electricity consuming country in the world about 1.54 trillion kWh per year.
- It consists of five regional and thirty state load dispatch centers, one of the complicated integrated network.
- A diverse category of people across the country such as socially, economically, religiously, culturally, etc.
- One of the fastest GDP (Gross domestic product) growth nation in the world about 6.68% with a global share of 3.28%. Its composition falls on three major sectors such as Agricultural (15.4%), Industrial (23.0%), and Service (61.5%).

By considering all these factors, it is expected that the impact of COVID among the Indian people influences the Indian electric market unswervingly.

4. Scenarios of Indian power system during COVID-19

4.1. Power sector during COVID

India is a vast country of over 1.3 billion people; therefore, the electricity demand is also very high, although it varies based on population density, geographical and industrial/commercial development conditions, etc. The power network is divided into five different regions; Northern Region (NR), Western Region (WR), Southern Region (SR), Eastern Region (ER) and North Eastern Region (NER) as shown in Fig. 11. The integrated power grid is supporting national electricity demand. India's Power System Operation Corporation (POSOCO) [63] oversees the national power grid. India has one of the most extensive synchronous interconnected grids in the world with an installed capacity of about 370 GW and regular base-load power demand is around 150GW. Industrial and agricultural consumption is around 40% and 20%, respectively, while commercial consumption is around 8%, whereas domestic load demand is around 30–32% [64].

Likewise, in other countries, the COVID-19 outbreak started in India too and the government started taking action from the middle of March 2020. In India, Janata Curfew was imposed on 22nd March, whereas nationwide lockdown started from 25th March 2020 and continued till 17th May (as per the recent announcement by Government). Fig. 12 shows historical developments of responses after COVID-19 spreading in India. Before the start of Janata Curfew, the energy consumption across the country attained a greater magnitude around 3500GWh. Subsequently, during the declaration, i.e., on 22nd March 2020, demand started to decay and obtained a value of about 3000GWh, continued its trend, and stretched lower most demand scale nearly 2500GWh on 1st

Table 1
Impact on the power system in various countries due to COVID-19.

Country	Population [55]	Lockdown period	Lockdown level	Electricity generation (GWh) [56]	Impact on power sector/government response	Ref
Spain	46,754,778	14-March-2020 to 25-April-2020	National level	275,000	• Power demand decreased by 3% and 24% in March and April-2020 compared to the same time demand in 2019 • More power generation by renewables, PV generation increased by 72%	[57]
Belgium	11,589,623	18-March-2020 to 19-April-2020	National level	74,600	• Industrial, commercial load demands more than 70% which had dropped substantially. • The government will provide financial support for the payment of energy bills. • A decrease in cash collection and an increase in bad debts for power companies	[57]
Netherlands	17,134,872	16-March-2020 to 28-April-2020	National level	117,500	• The overall energy demand has decreased subsequently.	[57]
Portugal	10,196,709	13-March-2020 to 11-April-2020	National level	59,900	• Drop-in demand will lead to economic loss to the power sector. Bad debt for the company will increase. • Government has taken measure to allow customers to pay utility bill later	[57]
Singapore	5,850,342	7-April-2020 to 1-June-2020	National level	52,900	• The overall energy demand has decreased subsequently	[58]
China	1,439,323,776	23-Jan-2020 to 8-April-2020	State Level (in Wuhan)	7,111,800	• Total electricity demand in January and February-2020 was 8% lesser than 2019 demand during the same period.	[59]
France	65,273,511	17-March-2020 to 11-May-2020	National level	574,200	• The planned energy generation of 380TWh in 2020 by nuclear sources will be affected. • The power sector faces approximately 70% revenue loss in March-2020 compared to march-2019.	[60]
Germany	83,783,942	20-March-2020 to 19-April-2020	State / City level (Bavaria)	648,700	• The overall energy demand has decreased subsequently. • During COVID the share of renewable energy increase to 41% which has contributed 302TWh.	[61]
India	1,380,004,385	25-Mar-2020 to 03-May-2020 [45]	National level	1,561,100	• It is estimated that Indian DISCOMs will suffer revenue loss of 4 billion US dollar and liquidity crunch of 7.2 billion US dollar during lockdown	[62]
Australia	25,499,884	23-March-2020 to (to be announced)	National level	261,400	• The commercial and industrial energy demand decreased by 7% and 1% respectively in Victoria. • Residential load demand increase by 14% in Victoria.	[30]
Italy	60,461,826	09-March-2020 to 3-May-2020	National level	290,600	• Power demand decreased 10.1% during March-2020 and 22% from 22-March-2020 onwards compared to the same time demand in 2019 • Renewable energy generation increased by 3.5% • Government has given relaxation for the payment of utility bills	[57]
United Kingdom	67,886,011	24-March-2020 to (to be announced)	National level	333,900	• Power demand at transmission-level decreased by 10% after 23-March-2020	[57]
United States	331,002,651	20-March-2020 to 29-April-2020 (for New York)	State wise (different for different state)	4,460,800	• Residential energy demand has increased by 20% in some part of USA. • It is estimated that in the year 2020 there will be 4.2% drop in retail sales of electricity to the industries.	[32]

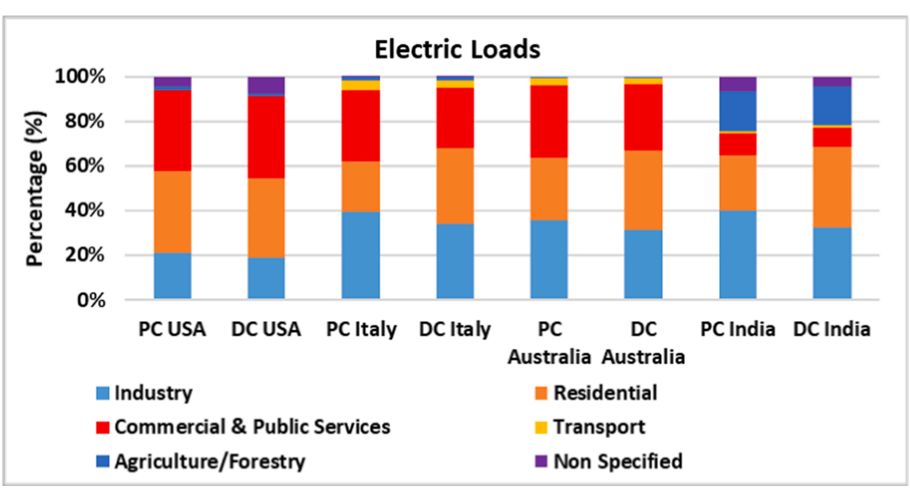

Fig. 3. Pre-COVID (PC) and During-COVID (DC) view of percentage demand of electricity load by major sectors [26,27].

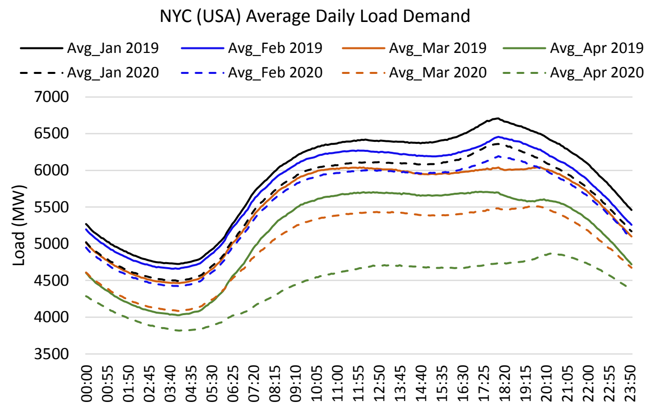

Fig. 4. Load demand in NY during COVID-19 lockdown period in 2020 compared to the same in 2019 [28].

domestic power demand.

4.1.1. Regional demand pattern

The regional energy consumption pattern, as shown in Fig. 14, exemplified that there was a sharp demand reduction in all regions between two periods (before and during the lockdown period). The load demand dropped in NER and ER is about 22.5% and 20%, respectively, which is comparatively higher than in other regions. Further, there is a notable drop in NER and ER when compared with 2019 energy consumption pattern.. Similarly, SR and WR showed a moderate drop of about 16% and 14.5%, respectively. Contrarily, NR, which stakes a higher part in all India demand, displayed the least drop of about 10%. This declination exhibits a significant demand reduction, which posed a severe economic and technical challenge to the power company.

From the above, it is stated that the integrated action of regional energy consumption, as well as power demand, demonstrates a similar pattern of national energy consumption or power demand. The comparative analysis of power demand between the regions during pre-COVID and during COVID is illustrated in Fig. 15. This interpretation demonstrates that there is a significant reduction in energy demand all over India due to lockdown.

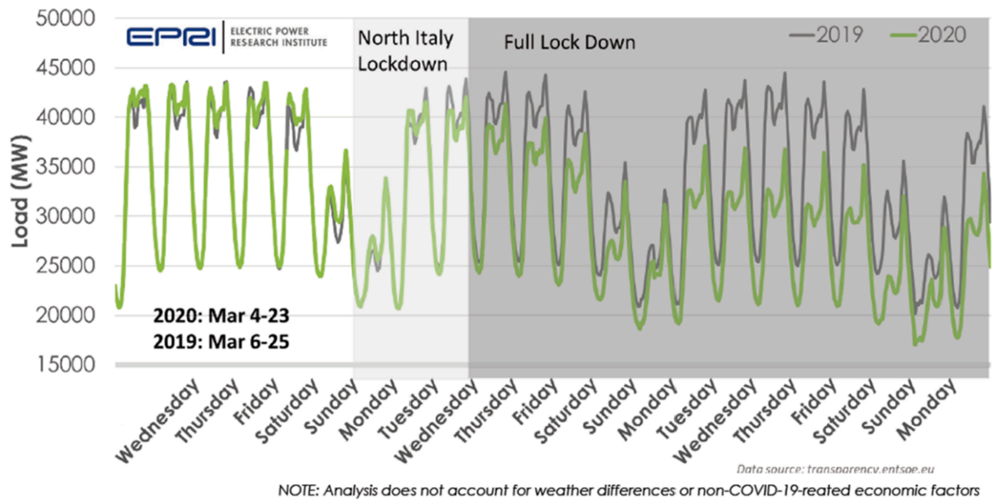

Fig. 5. Load demand in Italy during COVID-19 lockdown period in 2020 compared to the same in 2019 [26].

April 2020. In a nutshell, the average all India daily energy consumption reduced by 1000GWh compared to that of 2019, as illustrated in Fig. 13. Consequently, the energy mix during the lockdown varies greatly, particularly, coal-based generation adjusted to compensate for reduced consumption giving higher priority to the RES generation by the distribution companies. Therefore, the power purchase cost also reduced to a minimum compared with the pre-COVID period due to the increase in

4.1.2. Generation scheduling

Generation scheduling analyzed the system network operations and

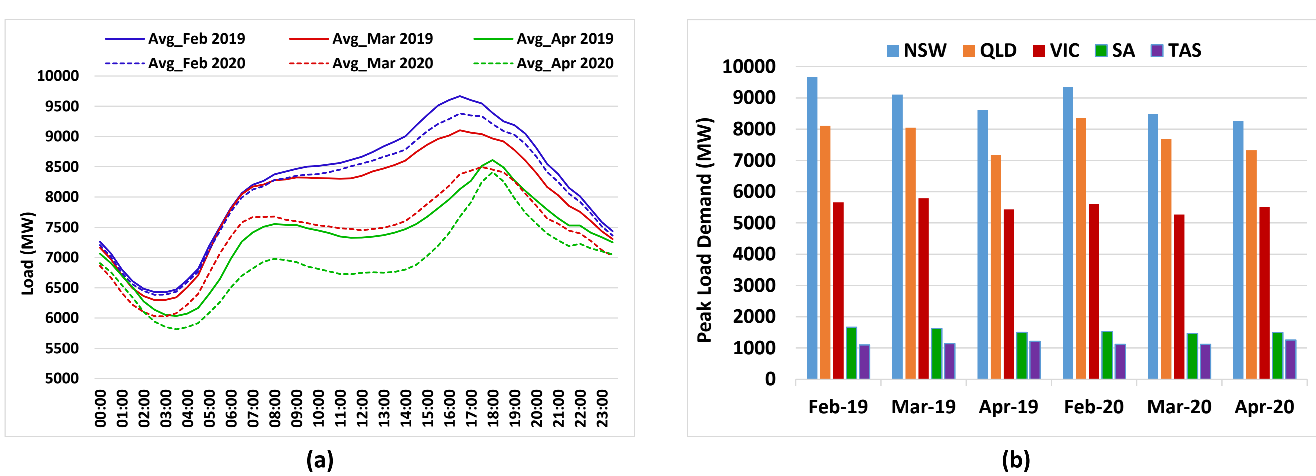

Fig. 6. Load demand variation (a) NSW Daily load profile (b) Peak load demand in Australian states in March 2020 and 2019 [29].

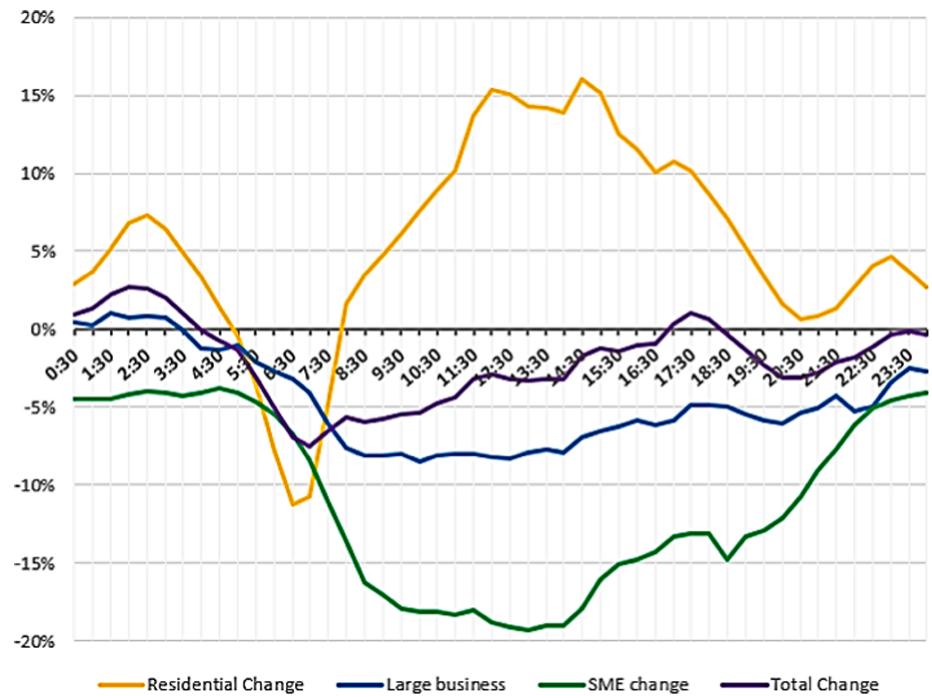

Fig. 7. Daily Demand Change in percentage in March 2020 vs March 2019 [30].

performed economic dispatch from each generating unit to optimize all India energy delivery with available constraints. The sudden variation in all India energy demand between pre-lockdown and lockdown periods wanted rescheduling of the generation pattern. Hence, POSOCO matched the new energy demand scale by shrinking the coal-based generating units, as illustrated in Fig. 16. Furthermore, the generating units of hydro, lignite, nuclear, gas, and RES are not shown any rescheduling in their magnitude (roughly) during the COVID period. However, there is a variation in RES (renewable energy resource) generation considering the availability of renewable energy resources such as solar irradiation and wind speed. Moreover, it is assumed that generation from roof-top solar photovoltaic (PV) was utilized maximum as most of the households were at home. Hence, there is a significant influence in the duck curve between Pre-COVID and during-COVID as displayed in Fig. 17. Additionally, the regional generation scheduling in all regions also reflects the same declination in load demand.

The mass reduction of demand patterns resulted to shut down some conventional generators based on fuel availability particularly thermal, gas and diesel power plants are operated economically. On other hand, a renewable energy source such as hydro, wind, solar, bio-gas, bio-mass and nuclear generations are utilized at maximum level considering the economic constraints and maintaining the must-run status to wind and solar generations. Under these circumstances, technical and operational challenges such as intermittencies, stability, voltage and system-balancing (both real and reactive power) problems are perceived due to the increased stake of PV generation. However, they could be resolved

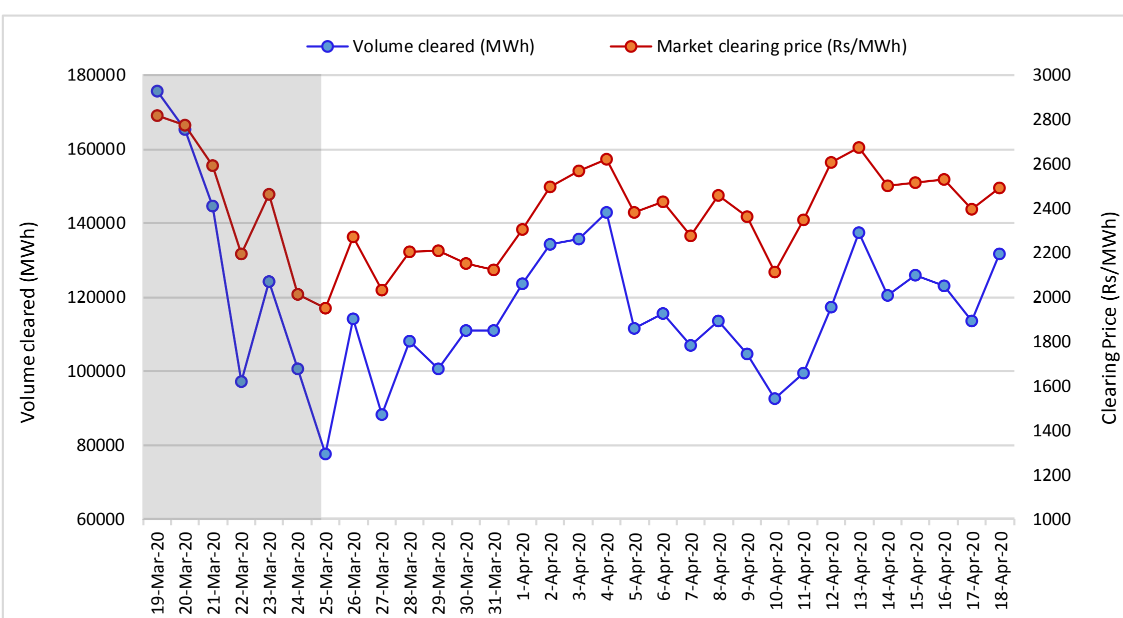

Fig. 8. Market Clearing Price (MCP) and Market Clearing Volume (MCV) in India.

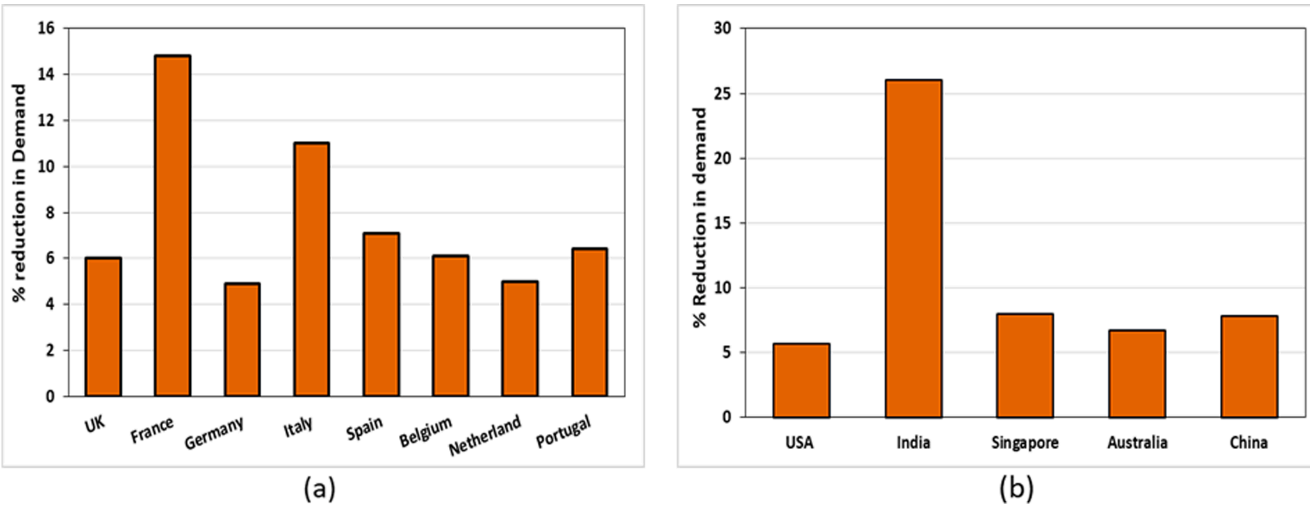

Fig. 9. Reduction in electricity demand (% change from 1st week to 3rd Week in March-2020) (a) European (b) Non-European countries [30,32–37].

with cautious forecasting, automated controls and other appropriate feasible technologies. This operating condition explores the possibility of adaptation of higher penetration of PV generation over the conventional generation in the future. Notably, India proposed to increase the installed capacity of RE power plant using wind and solar and targeted to achieve 225 GW by 2022 and 400 GW by 2030 [66].Therefore, the penetration of PV in grid would take the upper hand in the future and this operating procedure and measures during COVID set a strong foundation to maintain the stability of the system when RES stakes at a higher level. Furthermore, POSOCO managed this diverse demand pattern effectively using generation scheduling to match the varied demand pattern with available generation capacity within the regional grids.

4.1.3. Frequency profile

During the dynamic behavior of power demand and their respective generation scheduling, retaining the grid frequency within the acceptable band would be a difficult task. The grid frequency mainly influenced by the large power stations while imbalance between demand and supply, line outages, and tripping on the grid. Merely, the frequency is the point of equilibrium between the power demand and the power generation (without considering losses).

Due to the high reduction in demand from the pre-COVID to the COVID period, the Under Frequency-based load shedding (UFLS) problem raised. It consists of automatic UFLS schemes with four stages of frequency setting such as 49.2 Hz, 49.0 Hz, 48.8 Hz and 48.9 Hz.

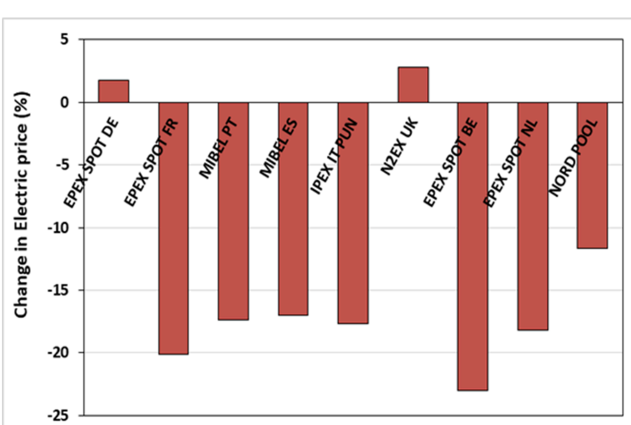

Fig. 10. Effect on Electricity Price (change from 2nd Week to 3rd Week in March 2020) in different European market [33].

Additionally, two stages of df/dt settings were adopted namely 49.3 Hz and 49.5 Hz. Both these schemes had been implemented for all regional grids such as SR, WR, ER, NR and NER. It is an important measure to maintain system frequency stability against severe disturbances. It helps in avoiding system collapse during significant disturbances like substantial loss of generation or loss of in-feed occurs on systems. Consequently, there is a backswing of frequency (generally above nominal) happening in the system. Frequency Variation Index (FVI) is illustrated in Fig. 18 which has seen that there is a severe FVI cause on 22nd March (start of COVID period) and 29th March, particularly due to steep load reduction and generation rescheduling. However, the adaptation of ULFS and df/dt relay schemes countered the mass disturbances and facilitated to maintain the stability of the grid during the COVID periods.

4.1.4. Inter-regional transaction

POSOCO operates all the five regional grids through NLDC using inter-regional transmission networks. The total inter-regional power transfer capacity of about 450 GW has been adopted at present. The power transaction between the regions representing two periods has been illustrated in Fig. 19. The negative and positive flow indicated in the plot characterizes the exporting and importing of power between two regions, respectively.

Exporting and importing of power between the regions are declined greatly during COVID due to a reduction in regional demand predominantly on the initial lockdown date. Since Regional generating capacity met the demand locally, power transactions from neighboring regions are very minimal. Additionally, the State LDC plays a vital role in scheduling and forecasting of generation for intrastate transactions particularly the infirm power such as Wind and Solar energy generation. It is expected to be injected into the Intra-State transmission network by engaging forecasting agencies if required. It helps to enable a better plan for the balancing energy resources required for secure Grid operation. The energy mix of firm and infirm contributes in balancing the generation and demand

4.1.5. Deviation Settlement mechanism (DSM)

Deviation Settlement Mechanism (DSM) is a mechanism the electricity regulatory commissions use to penalize the developers in case they deviate from the declared generation beyond a certain level (typically +/− 12%). This ensures the grid stays stable and there is no over drawl/injection or under drawl/injection from the schedule. DSM accountability is linked with frequency. As per the CERC regulation and procedure, the DSM procedure is strictly monitored by NLDC, SRLDC and SLDC. The DSM charges are calculated on a daily, weekly and monthly basis based on frequency variation. On behalf of the developer,

Fig. 11. Geographical location of Indian regional and state operative centers [65].

a developer or a Qualified Coordinating Agency (QCA) would be held responsible for forecasting and declaring the day and week-ahead renewable power generation for each pooling station or each generating station. Each developer is then allowed six revisions on the day ahead of schedule in close coordination with the load despatch agency and also the schedule should not deviate much with their actual (ACT) and scheduled (SCH) generation.

Fig. 20 displays the DSM of all five regions with their actual (ACT) and scheduled (SCH) generation. During the COVID period, the DSM between the actual and scheduled power was not in the phase due to the condensed demand pattern across the country. Particularly, SR and NR show a higher rate of deviation between two periods. Nonetheless, NER, ER, and WR retain the rate of deviation in typical fashion between both periods. It represents that the respective SLDCs effectively executed the DSM throughout the periods. It represents that the respective SLDCs effectively executed the DSM throughout the periods through Intra-state transaction by means of self-consumption of power within the state from Solar and Wind generators connected in the network.

4.1.6. Restoration of feeders

The post COVID activity increases the load demand particularly from the restart of Industrial and Railway loads. Therefore restoration of the system to normal operating levels might be a crucial task. Nevertheless, the adaptation of gradual restoration of the lockdown would support the power engineers to restore the feeders effectively. However, it is expected that the utility takes additional days to attend the issue and restore the feeders to normal working conditions because of the impacts of pre-lockdown due to COVID. The extended delays and increased loss of energy could be due to the shortage of workforce in substations, lack of necessary coordination of internal teams of the utility, insufficiency of spare parts available in the market, lack of conveyance or transportation facility and time is taken to issue line clear for taking restoration work, especially in distribution circles. Additionally, the following steps/ measures might be adopted to enhance the restoration process.

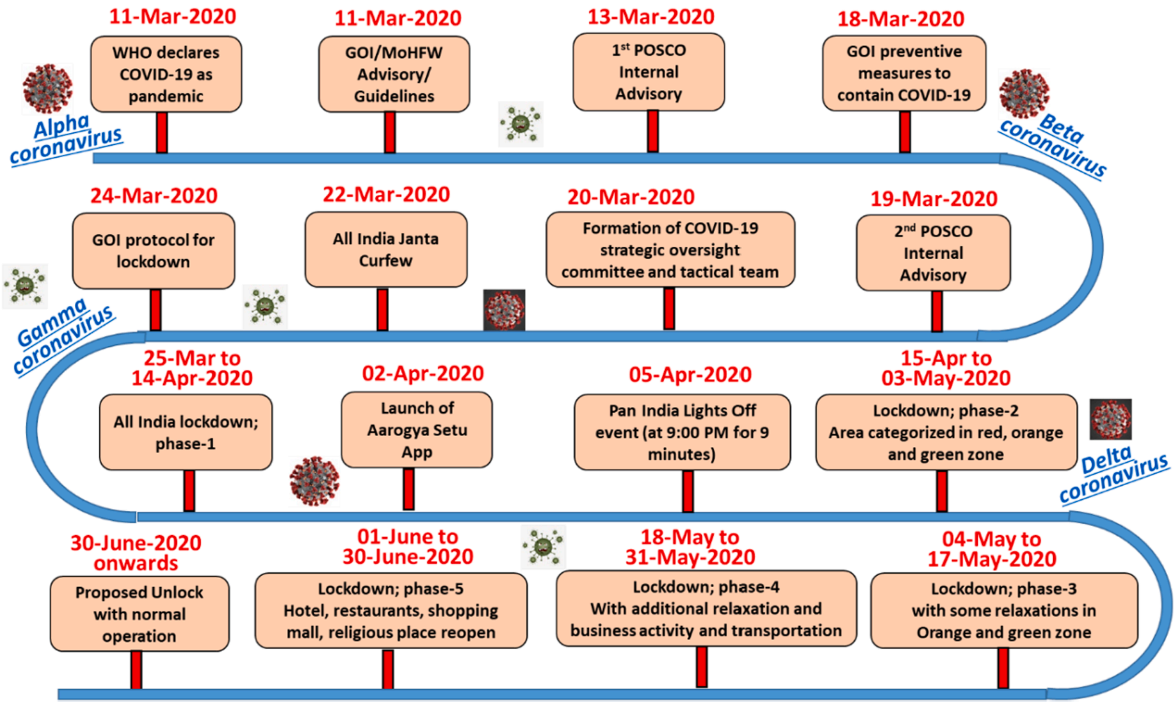

Fig. 12. Activity of Indian government against COVID-19 [63].

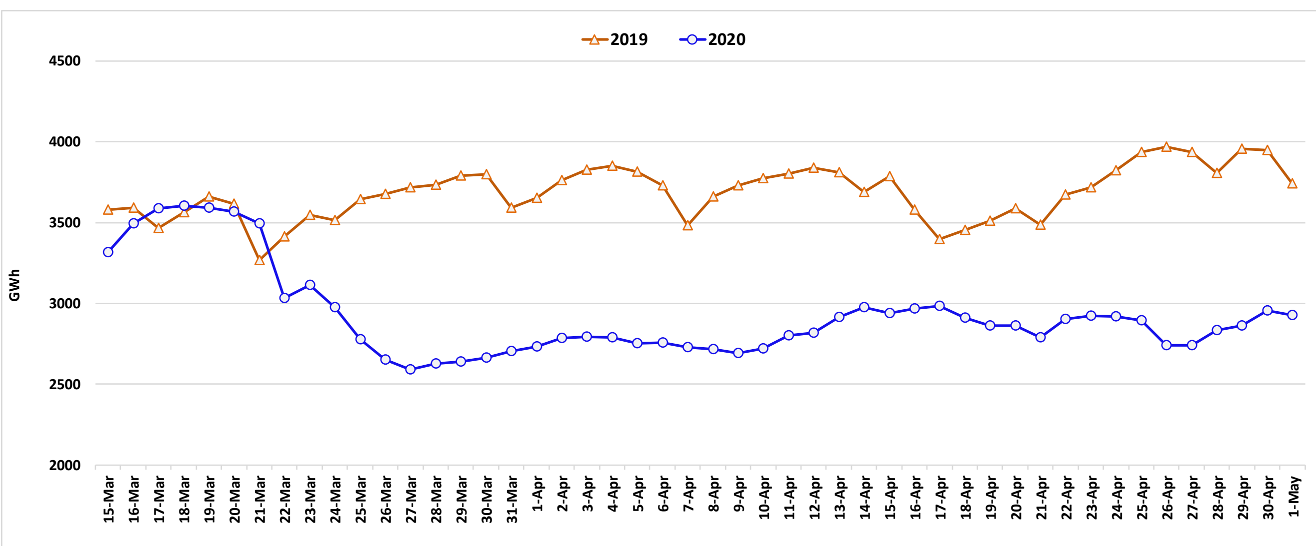

Fig. 13. All India Energy Consumption in GWh.

- Using the operating reserve, the system operator may meet out the demand during shortfall in generation within a period of time from available generating capacity.
- Adopting a spinning reserve by adding extra generating capacity which is made available by increasing the power output of generators that are already connected to the power system (online).
- Using the hydropower and gas turbine generators to meet out the demand for immediate restoration of feeders.
- Adopting extra generating capacity that is not currently connected to the system but can be brought online after a short delay (non-spinning reserve or supplemental reserve) for isolated power systems (typically meet out the power available from fast-start generators).
- Assessing the generators that intend to provide either spinning or non-spinning reserve that should be able to reach their promised capacity within roughly ten minutes.

4.2. *The light-off event in India*

The Prime Minister of India requested its citizens to turn off their lights at 9 pm on 5th April 2020 for 9 min to enumerates the country's fight against the COVID-19 pandemic. The nations gladly accepted the call and participated in the event. This sudden change in load reduction, as well as increase after the event, could have a significant impact on the grid.

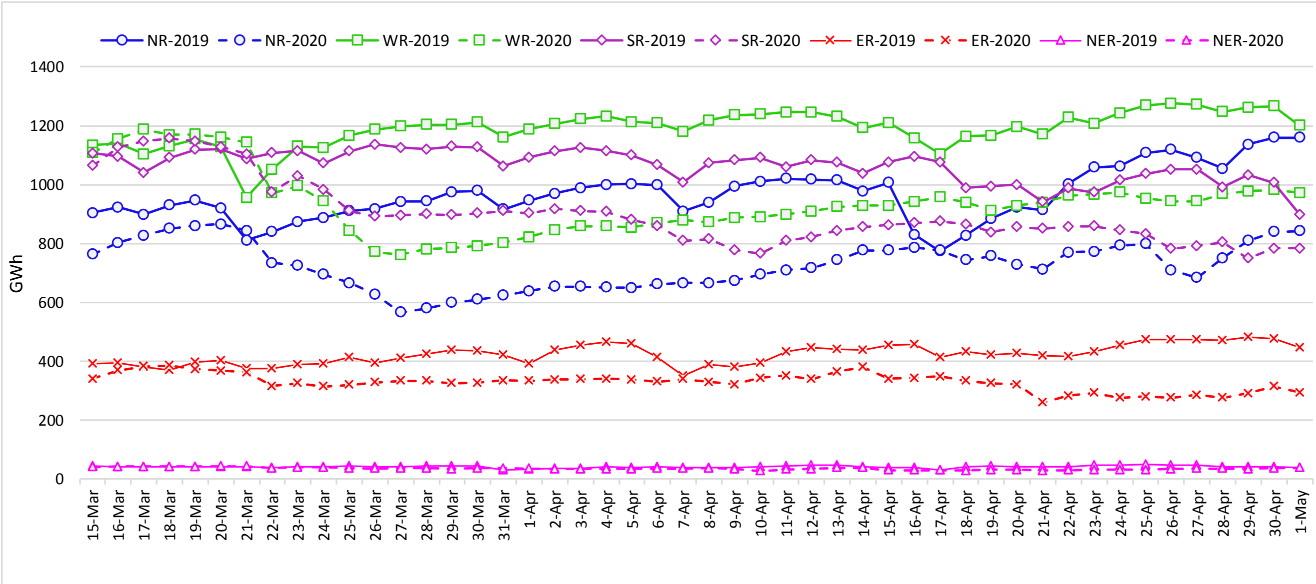

Fig. 14. Region-wise energy demand in GWh.

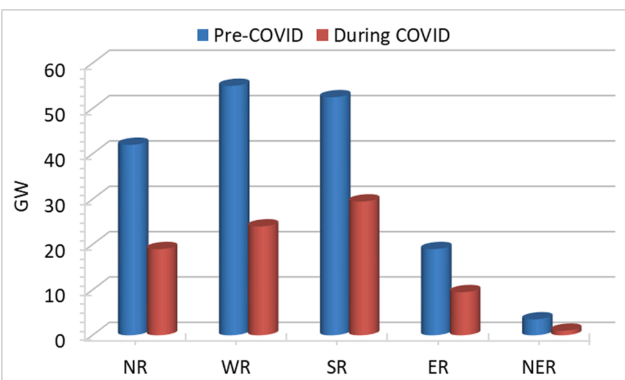

Fig. 15. Load demand reduction during COVID-19 in GW for the regions.

4.2.1. *Preliminary exercise*

To ensure the reliable and secure operation of the system during the event, mock exercise was planned on 4th April 2020 (before the actual event date) to estimate the actual load reduction during the upcoming event. It is an essential task to compute the total load reduction or all India lighting load to conduct the preliminary test. Therefore, estimation of load reduction was figured using two methods as follows:

- All India load reduction for the actual event was calculated based on the demand pattern of 29th March 2020 particularly considering the evening peak. It had been perceived that all India demand was around 101207 MW at 18:07 h and later it was increased up to 112551 MW at 21:00 h. Considering this scenario, it was predicted that the all India lighting load would be around 11344 MW (difference of demand at 18:07 h and 21:00 h).
- Another exercise was adopted to estimate the all India load reduction based on the summation of household consumers from different SLDCs. It was recorded about 15085 MW.

Considering these two reports, it was concluded that the total all

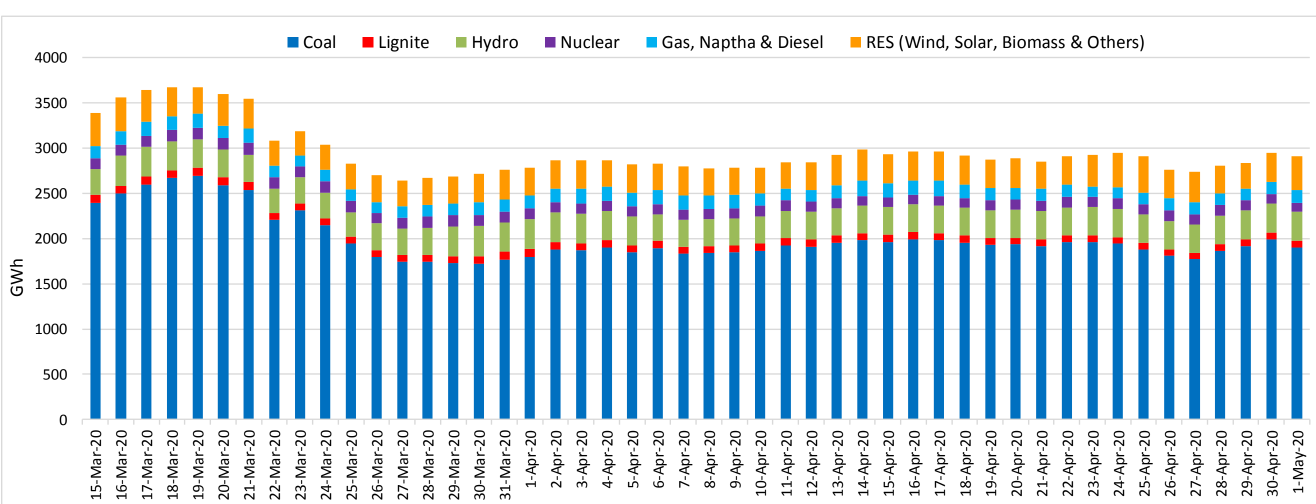

Fig. 16. All India Generation Scheduling (Fuel wise) in GWh.

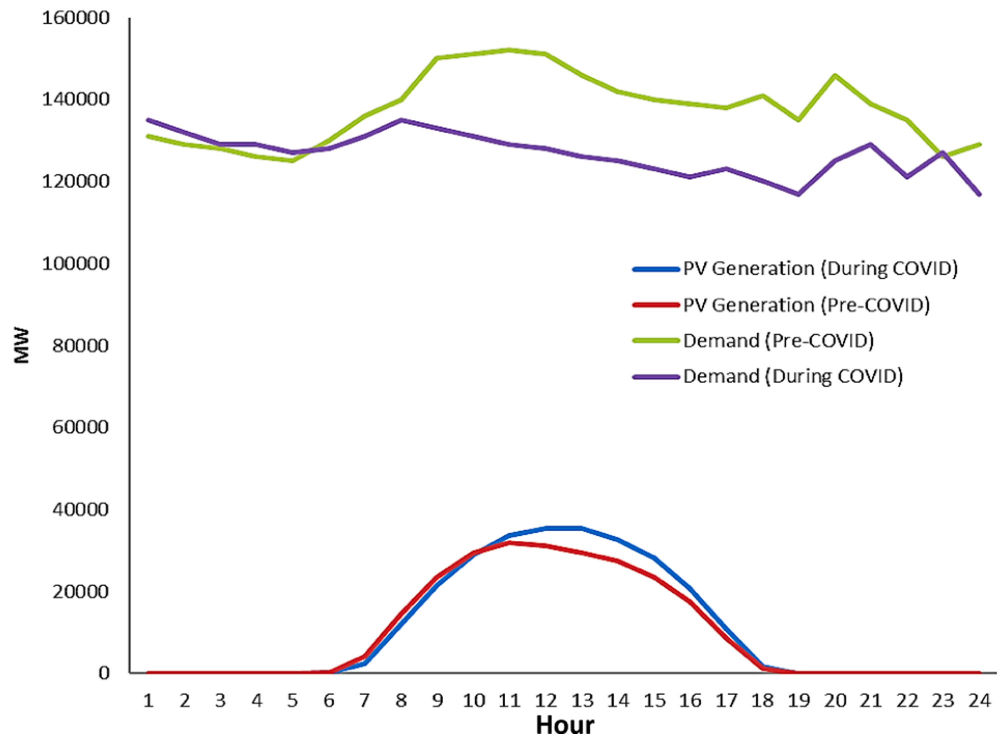

Fig. 17. Duck Curve Pre- and during COVID-19 period.

India load reduction would be around 12–15 GW and might be taken place for 2–4 min. Subsequently, necessary precautionary measures/arrangements were made before the start of the mock exercise. Some of them are as follows [45]:

- All the substations, generating plants and distribution centers are synchronized to Indian standard time (IST).
- Hydro generations were conserved during evening peak hours for flexibility during the mock exercise.
- Advance actions such as switching off transmission lines, taking reactors in service, changing SVC, STATCOM, HVDC set points, etc. were taken before the event for keeping voltages and line loadings within permissible limits.
- Capacitor banks were kept open at the distribution level to maintain the nominal voltage.
- Discoms are restricted for switching operations of feeders.
- All defense mechanisms namely Under Frequency/df/dt relays and Automatic demand management systems were kept in service.

The operational guidelines were finalized as indicated above and the mock exercise was adopted on 4th April 2020. The observed actions and results are as follows,

- Before five minutes i.e. 20:55 h, thermal ISGS (Interstate generating stations) were condensed gradually about 60%.
- Hydro generations were ramped up from 20:57 h to balance the demand.
- Ramping up of thermal units were carried out form 21:05 h.
- After stabilization i.e. 21:09 h, hydro units were withdrawn from the grid.

During the complete process, the grid frequency maintained between 49.50 Hz and 50.50 Hz from 20:45 h to 21:30 h. Also, seven 764 kV and nineteen 400 kV were exceeded the voltage limits

4.2.2. *Actual event*

The actual Light off event happened on 5th April 2020 from 21:00 h

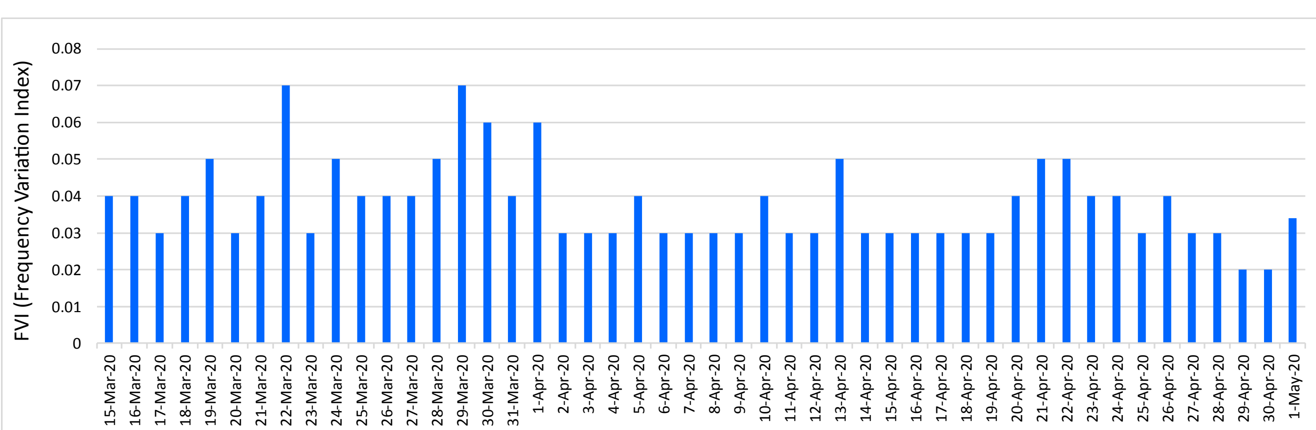

Fig. 18. Frequency Variation Index (FVI).

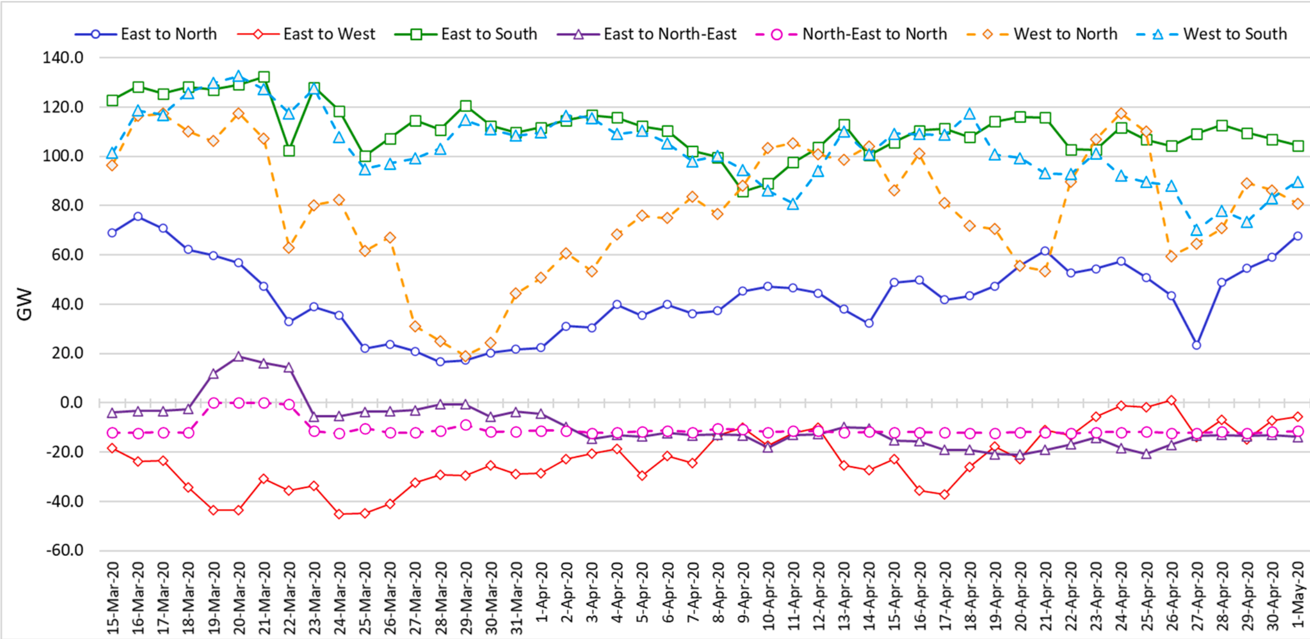

Fig. 19. Transmission corridor flow in GW.

onwards. The preliminary arrangements were made as per the mock exercise. The observed scenarios are discussed in detail as follows:

- The total reduction in all India demand recorded during the event was 31089 MW. All India demand started reducing from 20:45 Hrs, and the minimum demand of 85,799 MW was recorded at 21:10 Hrs as shown in Fig. 21. Subsequently, from 21:10 Hrs, the demand started picking up and settled at 22:10 Hrs with a demand of 114400 MW.
- Grid Frequency during the event remained in the range of 50.26 Hz to 49.70 Hz with a maximum recorded at 21:08 Hrs and a minimum at 20:49 Hrs.
- As the sudden change in huge load may have a severe impact on the network therefore POSOCO took some actions to better handle the above light-off event.
  - After the evening peak, the thermal generation has reduced while hydro generation was increased to manage the demand. Hydro started to ramp down to 17543 MW (from 25559 MW to 8016 MW)

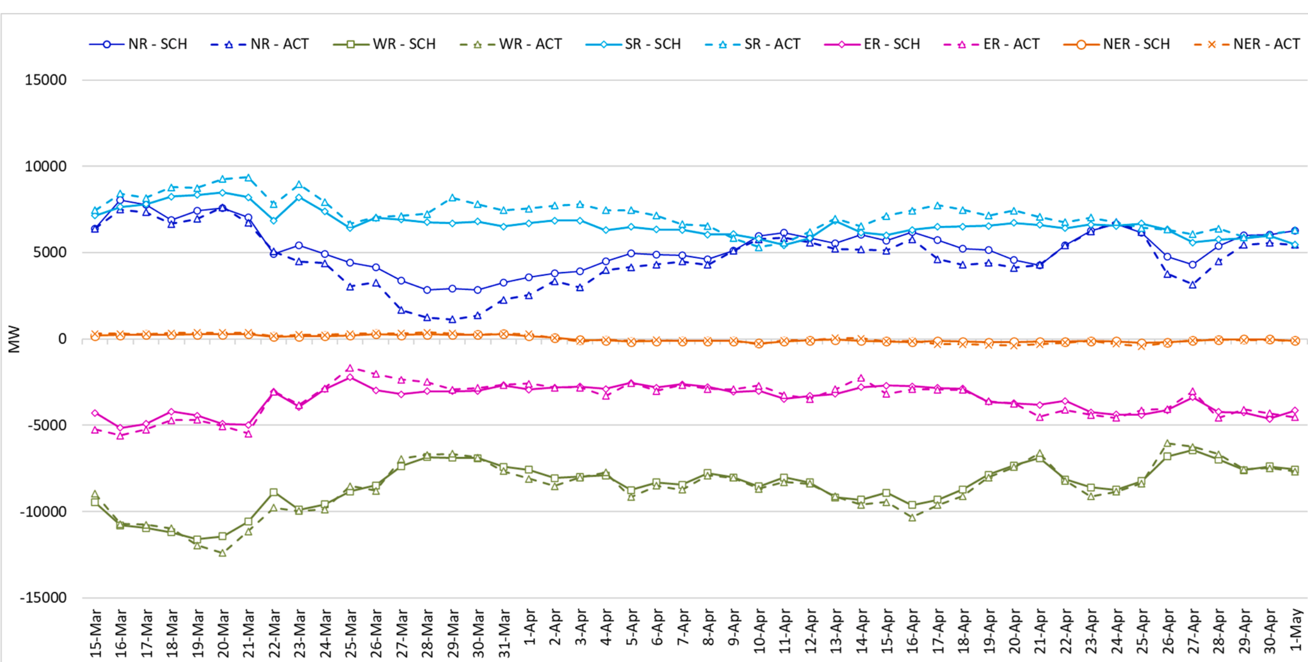

Fig. 20. Deviation settlement mechanisms.

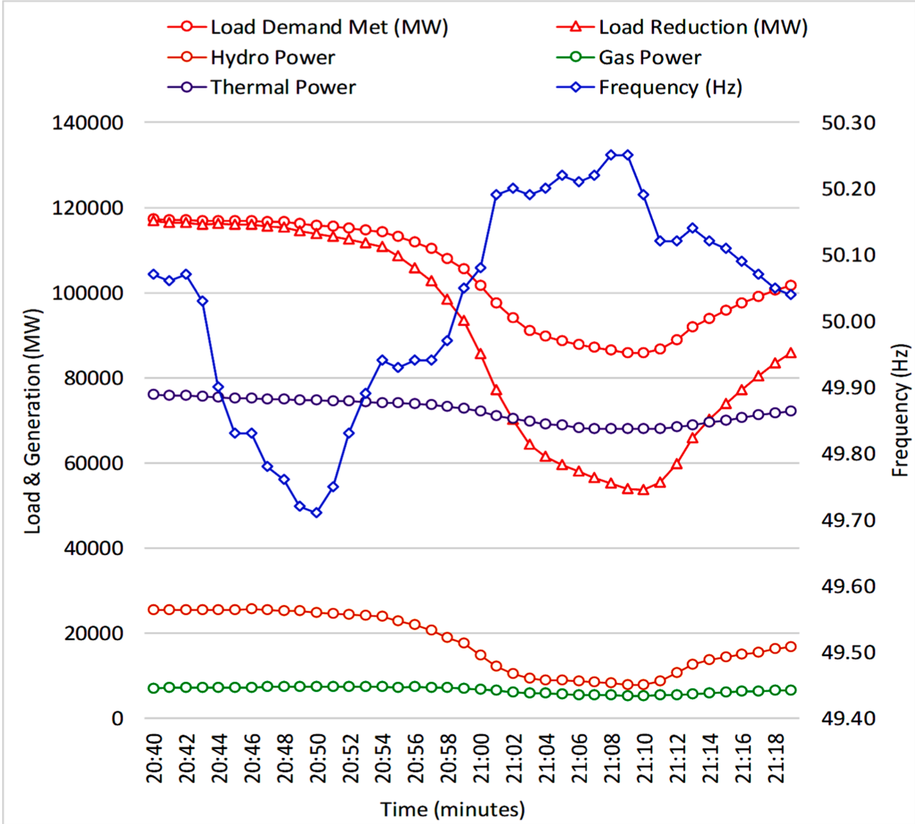

Fig. 21. Demand and frequency drop during the light-off event.

at 20:45 hrs. This hydro generation was again ramped up from 8016 MW to 19012 MW from 21:10 Hrs to 21:27 Hrs to meet the increase in demand after the event.

- Reduction of total 10950 MW generation was achieved through Thermal (6992 MW), Gas (1951 MW) and Wind generation (2007 MW) from 20:45 Hrs to 21:10 Hrs.
- Advance actions such as switching off transmission lines, taking reactors in service, changing SVC, STATCOM, HVDC set points, etc. were taken prior to the event for keeping voltages and line loadings within permissible limits.
- The event was managed smoothly without any untoward incident, while power system parameters were maintained within limits. POSOCO acknowledges the support and co-operation of all the stakeholders in successfully meeting this unprecedented challenge.

From the descriptions of the Indian case study, it is revealed that the demand pattern during the COVID-19 decreased extensively. However,

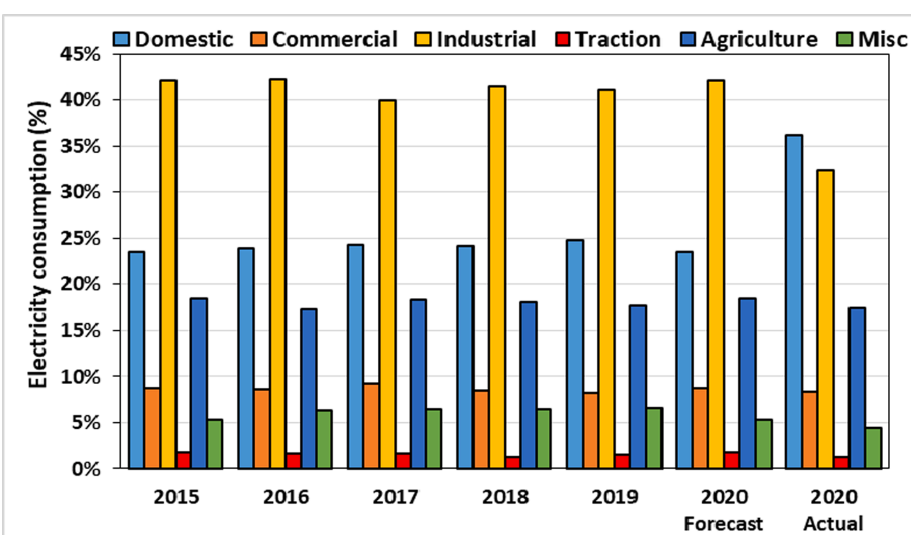

Fig. 22. Electric energy consumption in different sector of India [67,68].

POSOCO managed this adverse circumstance and retained the grid frequency and voltage profile within their recommended band. Nevertheless, they confronted a few issues and challenges during the COVID period, as discussed in Section 5.

5. Socio-economic and technical challenges observed in Indian power system

Due to COVID-19, one of the major sectors operating 24 × 7 and influenced on a real-time basis is the electric power system. Due to the stagnation in the operation of businesses, industries, and transportation in response to COVID-19, the Indian energy demand pattern declined vigorously. Particularly, the industrial and commercial load demand has declined sharply while domestic load and electric load at hospitals/ emergency services have increased significantly. The change in load pattern has caused not only a financial burden on the power sector but also enforced many issues and challenges considering socio-economic and technical perspective.

5.1. Socio-economic issues and challenges

- **Economic losses**

Fig. 22 presents the percentage share of electricity consumption of different sectors in India from 2015 to 2020, including the forecasted and actual load demand for 2020. Due to the nationwide lockdown, particularly from 25-March 2020 to date, the industrial, commercial, and traction load demand has fallen significantly. It reveals that the domestic load demand has increased from 23.53% to 36.15% whereas the stake of the industrial load has decreased from 42.1% to 32.34%. This deviation has a noteworthy impact on the revenue of power agencies because power sector companies/utilities make a major profit from industrial, commercial, and traction load, whereas domestic loads are supplied at a subsidized rate and hence it consequences a heavy financial burden in the Indian power sector. Table 2 illustrates the electric tariff rate for the various sector at the national capital Delhi, India, for instance.

POSOCO pointed out that total demand during the lockdown, particularly between the first weeks of lockdown, was 18 kWh billion units while the week before the demand was 23 kWh billion. Roughly about 21.7% of demand has been reduced. Further, it could consequence in extra demand compression of 15–20 billion units in the upcoming weeks. It reflects net revenue loss of IR25,000 to IR30,000 crores for the Distribution companies. Furthermore, the average clearing price has condensed from IR2.15 to IR1.95 per kWh. Moreover, energy consumers are also affected by COVID-19 and may not be able to pay the energy price. However, the Indian government has sanctioned a financial relief package for the distribution companies by providing a three-month moratorium. Also, the payment security amount has been slashed by half for future power purchases.

- **Reduction in electric bill payment capability by a section of society**

Due to closures of industries and businesses, people are not able to go out for work; this will impact on their salary. In such a scenario, a large section of the society is struggling and focusing on basic amenities and hence, incapable of paying the electricity bill. This directly affects the revenue and bad debt of the power sector company. Any shortfall in revenue may increase electricity tariffs in the future or a burden on the power sector company/government.

Table 2
Electricity tariff rate (for FY 2019–20) [69].

Category	Fixed charge (IR/KVA/month)	Energy charge (IR/KWh)
Industrial load	250	7.75
Commercial load	250	6.00
Domestic load	150	4.50
Agriculture load	125	1.50

- **Delay in upgradation/transition-related activity in the power sector**

Due to COVID-19, the up-gradation and transition going in the power sector may get delayed. Due to the slow growth of economic investment by the public and private sector may decrease, which may affect the pace of transition.

- **Financial liquidity crunch and delay in the sourcing of materials**

Due to delay and less revenue from the DISCOMs, the under-construction projects will face financial liquidity crunch and delay in the sourcing of materials and construction activities. Due to lockdown, it is estimated that Indian DISCOMs will suffer a revenue loss of 4 billion US dollars and a liquidity crunch of 7.2 billion US dollars [70].

- **Delay in manufacturing and installation of renewable project**

Indian import of solar panels and modules from China in FY17, FY18, and FY19 are $2,817.34 million, $3,418.96 million, and $1,694.04 million, respectively [71]. Due to India's dependency on China for the manufacturing of solar photovoltaic panels, Indian solar segment manufacturing companies are going to face delays in the procurement of material from China [72]. Even post COVID-19, due to the non-availability of labor due to their movement to native places and disturbance in the supply chain, there will be execution delay in the functioning of the solar manufacturing sector. For many other planned and undergoing renewable energy projects, several materials/parts are imported from the USA, China, and other parts of Asia. Because of disturbance in the manufacturing and supply chain in many of these countries, there will be a delay in the renewable energy project in India. Also, due to the pandemic, there is a collapse in crude oil price and there is a financial problem globally, which also affects the rapid growth of the renewable energy industry.

- **Reduction in subsidy and investment on renewable energy by the government**

Due to the health and economic crisis caused by COVID-19, the government will have priority and focus on reviving the Indian economy at earliest. Thereby, there is a possibility of a reduction in subsidy on renewable energy-related researches and projects.

- **Illness among power sector workforce**

The electric power sector is the Organization that works 24 × 7 all around the year. To make it operational skilled people associated with the power industry have to come out of their home even during the lockdown and hence, there is a possibility of illness among the workforce. This directly affects the health of co-workers and the performance of the power sector industry.

5.2. Technical issues and challenges

Due to lockdown, there are many technical issues observed in the Indian power networks, including voltage and frequency unbalance, overloading of a substation, modification of duck curve, etc. To tackle these issues to ensure the smooth operation of the power systems, the responsible agencies, for example, POSOCO has initiated disaster management planning, including many measures and initiatives.

- **Voltage control measures during COVID period**

The sudden reduction of load demand during lockdown causes overvoltage in Transmission and Distribution Networks. Hence, dynamic voltage control takes place at the interconnection and the transmission level.

The major tasks at the interconnection network-level related to voltage control are:

- To retain a constant voltage at the power stations
- To maintain a stable distribution of reactive power throughout the networks
- To preclude overvoltages due to load outages
- To raise the grid stability at short circuit situations by swelling the excitation to maintain the synchronism of the grid.

The following precautionary measures were made by RLDCs to prevent the overvoltages during the lockdown period:

- All the reactors are put into service for overvoltage control to maintain the grid stability.
- Static compensators and Static VAR Compensators were kept in voltage control mode.
- Capacitor banks were kept off at distribution level to prevent overvoltages at consumer points.
- Thermal Generators were adopted to absorb reactive power during the high voltage condition.
- Solar generating stations were equipped with STATCOM devices; it absorbs the reactive power during the non-generation period and high voltage conditions.
- Capacitor banks were equipped with Wind generators and inject the reactive power to the system for grid stability.

Due to preceding precautionary measures, the Voltage Deviation Index (VDI) during the lockdown in all major substations displayed a reduced index, compared with the earlier month, as shown in Fig. 23. It reveals that the measures are taken by RLDCs consequence a great voltage control, particularly for dynamic load patterns.

- **Huge demand variation and power procured through IEX**

The COVID-19 calamity has logged 25% declination in national peak power demand during a lockdown. It consequences a disparity between demand and supply during any part of the day. This could upset the disposal of power to critical sectors, particularly for healthcare. To ensure reliable operation, IEX's forecasting techniques have been adopted for flexible trading in blocks of 15-minutes. It supports the ecosystem to stabilize the demand–supply schedule on a real-time basis. This 15-minute trading block permits distribution sectors to acquire power as per the varying demand during 96 different time blocks per day. For illustration, southern distribution procured 345 MW during a time block (14th April) then ramped up to 1,800 MW during an alternative time block.

- **High-cost generator is put into stand by condition**

One of the major actions taken by utilities due to reduced energy demand is to place the high-cost thermal power plant in standby or shutdown conditions. The optimization measures have been taken based on the demand requirement allowing all the low-cost generators to run in its full load while others are on a fractional level.

- **Voltage issues**

In the Indian grid, various voltage levels from 11 kV to 1200 kV are available throughout the network to efficiently supply power to the consumer from generating stations to the load centers. During the COVID, most of the power transformers and transmission lines are allowed to run in under loading conditions to tackle with the reduced demand. This consequence of voltage issues-particularly at high voltage level. To overcome these issues, reactors are committed to service, and capacitor banks are de-committed from the service.

- **Protection aspects**

The most effective defense mechanism, such as under frequency relays and differential relays are adopted in the national grid for protection of generator, transmission lines safety, and system stability purpose with the help of mock exercise.

- **Interruption of power connections**

The state authorities instructed the subordinate department not to interrupt the power connection in the state for non-payment of electricity bills until further notice for all categories of consumers. This amendment also indicated to postpone the recovery of fixed / demand

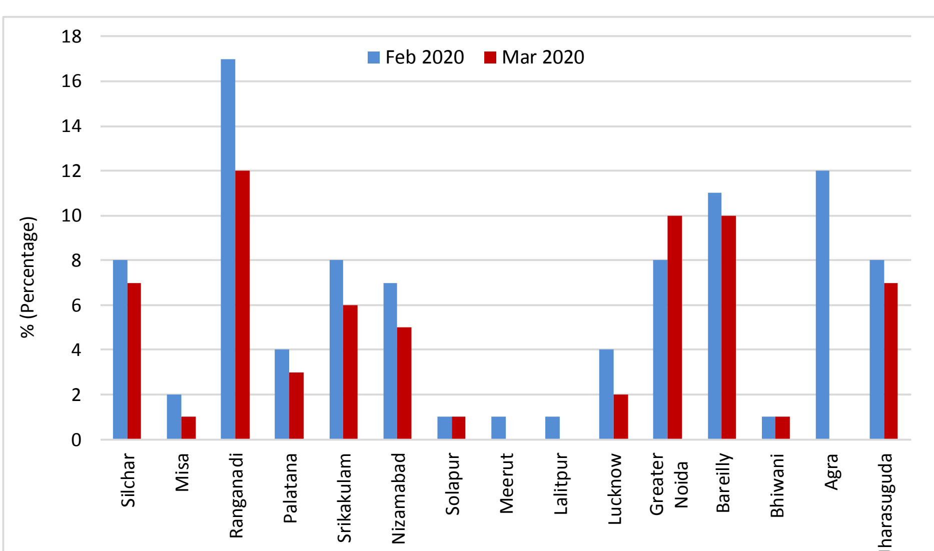

Fig. 23. Voltage Deviation Index (VDI) between pre- and during COVID-19 period.

charge towards power consumption. This consequence poses an additional financial burden to the power companies.

- **Fuel availability**

Since transportation in India is utterly aborted during the lockdown, import or export of fuels for power plant operations, particularly coal transportations was not functional.

- **Cybersecurity**

Due to the pandemic situation, the utility employees are working remotely i.e. work from home which acts as the number-one priority for utilities to continue their operations effectively. But, this activity also leads the utilities to new cyber-risks that might be from inside and outside the walls of its cybersecurity mechanism. This new approach of accessing the plant production and grid networks from homes raises the risk of outages and safety events as attackers can easily access the remote systems through the insecure network connection. In order to avoid such a cybersecurity crisis during this pandemic, utilities should ensure the baseline defense mechanism by changing the cybersecurity architecture [73]. Also, the Indian power utility should strengthen the cybersecurity mechanism by reforming the following frameworks

  - **Institutional framework:** For ensuring compliance of legal, contractual, and technical framework to make the system nearly 100% secure from cyber-attacks.
  - **Legal framework:** To integrate several mandatory provisions for compliances from procurement to installation to operation.
  - **Technical framework**: The security policy needs to be evolved to improve the technical framework for the operation of the system to ensure cybersecurity.

The Government of India, under the Information Technology Act, 2000 and the Reasonable Security Practices published in 2011 enforces that all organization requires to comply with the ISO:27001 to ensure security and safety of the organization [74]. National Thermal Power Corporation (NTPC), National Hydroelectric Power Corporation (NHPC) and Power Grid Corporation of India Ltd (PGCIL) have identified their infrastructure in respect of business criticality and implemented ISO 27001 controls.

6. Recommendations and suggestions

Due to the unlikely situation, the power and energy sector has been hit badly in almost all the countries in the world. Energy Quest, in its March 2020 quarterly report, wrote: "*Nobody knows how COVID-19 would pan out, whether it would be quickly contained or become a true pandemic, but it is likely to hangover the energy sector for most of this year*" [75]. As our lifestyle now experiences a shift due to the steps taken to battle the pandemic situation, our energy usage profile has been shifted accordingly. This pattern would continue to stay based on the stringency of lockdowns. This section proposes some crucial steps that need to be recognized and undertaken straightaway to continue operating the energy sector in a healthy manner worldwide. Some recommendations presented in Section 6.1, adopted from the lessons learnt during the challenging periods in various parts of the world including India, would help utilities to handle the current challenging scenario. The recommendations presented in Section 6.2 need to be taken up to overcome impacts arising from any unforeseeable pandemic alike scenarios in future and thus continue supporting the sustainable growth in the sector. Some recommendations would help utilities to handle the current scenario and the rest recommendations need to be adopted to overcome future unforeseeable pandemic alike scenarios, gradually. A quick snapshot of the proposed recommendations is shown in Fig. 24.

6.1. Issues to look at right now: During COVID-19

Logically, every utility has enabled its disaster management plan to combat with the current scenario. However, an event like the COVID-19 pandemic situation is something no one could ever imagine of. Even a robust management plan struggles to handle the current energy scenario, which in other predicted disaster cases could have worked efficiently. Starting from taking maximum precautions for the employees working in the power sector on or off the field to ensuring proper health check-up facilities is a must to operate the power stations and control centres effectively. To run the power sector safely and securely, we cannot afford the luxury to overlook the following issues.

- **Ensuring maximum safety of employees:** To keep the power plant and control centre safer, the use of disinfectants around the place is a must. Where a 24-hour service is required, staffs would be assigned roaster duties in shifts so that if a team gets affected, the whole team can be kept in quarantine and other teams can take over the charge. The engineers and workers working at power supply facilities must be motivated through a declaration of proper financial and risk packages.
- **Technical operational strategies:** As soon as the demand plunges, electric utilities should take immediate measures to operate the grid in an optimum way yet ensuring maximum system stability and reliability. Utilities should utilize the low-cost generators utterly and de-commit the high-cost generators gradually without losing the grid stability. The power sector should immediately compute the availability extent of sources such as coal, gas, diesel, nuclear fuel, and water resources. To ensure grid stability, thermal power plants should be considered for baseload generation. Upon availability, hydropower stations might be utilized during peak periods and based on the water availability, might operate continuously. The utility should consider an economic trade-off between operating the thermal generators below its optimum operating point with low efficiency and operating few generators at higher efficiency while shutting down other generators. Solar and Wind generators might be utilized to harness its full potential.
- **Adapting to the changing Duck Curve:** If observed, COVID-19 is changing the duck curve within the network due to the cases of high penetration of rooftop solar in urban areas. This is observed in many utilities during this lockdown period because prosumers are consuming the maximum of the generated power at home due to the 'stay at home' policy, and thus power sell to the grid is lower which makes the curve shifted upward. Utilities must adapt to this new shape of the curve and schedule the grid generators accordingly, which would require the utility to run a new economic dispatch program.
- **Consumer interaction:** During the crisis period people need to stay at home and thus it is must that utility ensure "people have access to reliable, affordable electricity to stay connected and continue to communicate with public services and one another remotely" [76]. For any type of customer service in such situations, the facility of remote login to home devices is advised to resolve technical issues and over the phone maintenance query and support is recommended. During this time, consumers may not be able to pay for the unpaid bills and recharge their pre-paid accounts due to the immobility condition. Hence, utilities should adopt a measure not to cut off the consumer due to a late payment issue or insufficient funds in his account. The utility should work on economic plans to adjust the dues in his future billing cycles, gradually considering the late payment fees are exempted.
- **Fully executing the Disaster Management Plan (DMP):** The power utilities should take initiatives to conduct an impact analysis so that none of the emergency and sensitive loads (e.g., most important govt. units, hospitals, clinics, medical facilities, pharmaceuticals, pharmacies, grocery shops, banks, etc.) get disconnected

due to any power interruption. The utility should consider any possible adverse weather events, such as storms or typhoons. During this period, the utility should concentrate on increasing the power system resiliency, prioritizing important workloads and assess the financial condition. The financial study should include potential revenue loss, potential future costs due to this event, minimizing unnecessary current costs, find out possible revenue generation scheme etc. For any reason, if the main control centre needs to be shut down, an alternative arrangement would be required to operate the usual business. Hence, the utility should consider setting up an additional temporary control centre facility and associated technical supports. Proper guidelines for using such facilities need to be developed and make employees aware of these measures is highly recommended. Every company has its DMP; however, a situation like COVID-19 was beyond the imagination. Hence, this situation is a lesson learned for organizations to prepare future DMPs so that eventual adaptation is assured.

- **Financial plan:** In due course, utilities must develop a model to assess the possible revenue loss and thus need to held conversations among the regulatory and policymakers regarding the financial

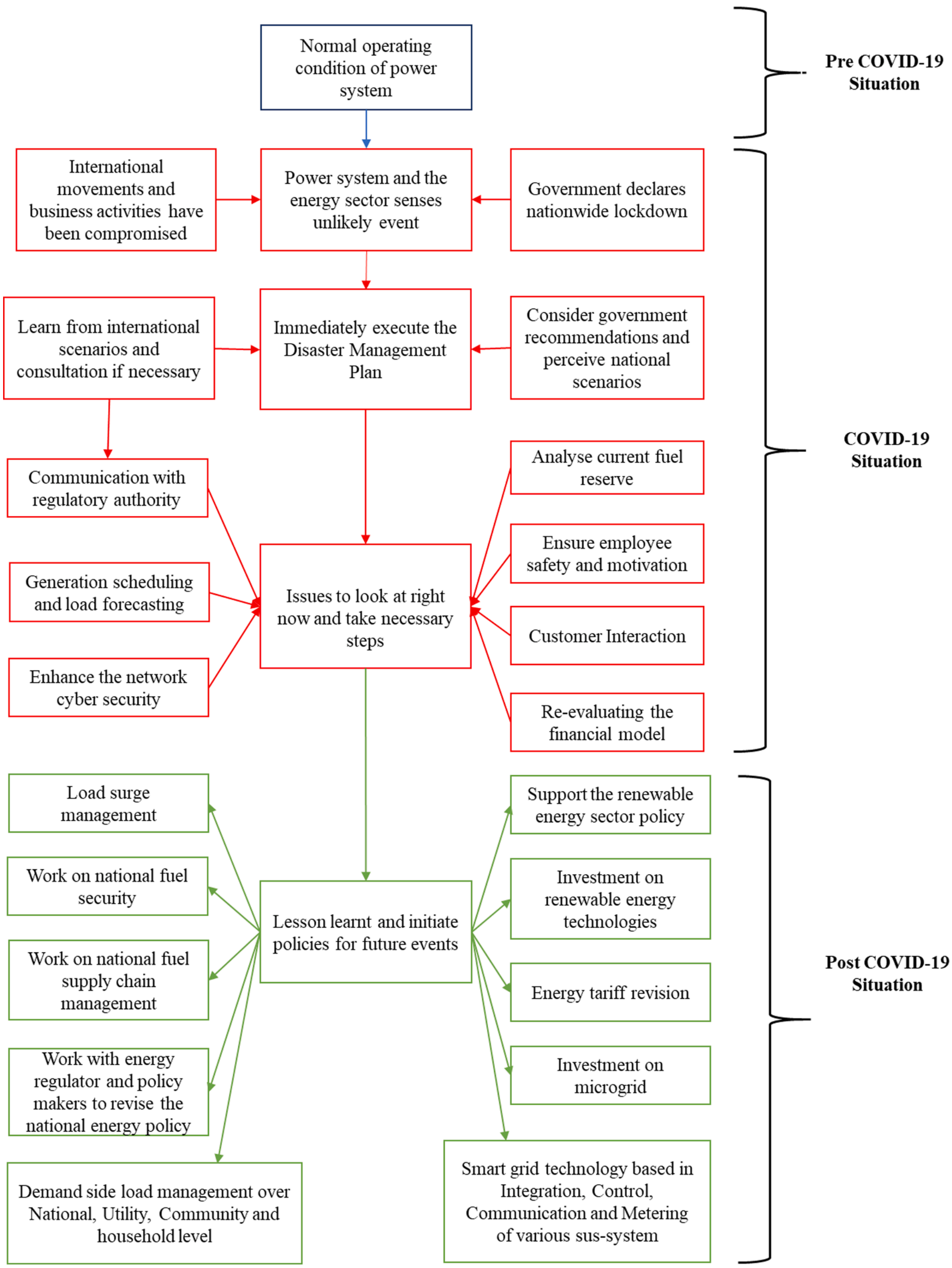

Fig. 24. Flowchart illustrating the recommendations on the operational and policy-oriented management of power and energy sector during the pre, during and post COVID-19 situation.

support from the government. The utilities do not have other businesses except providing electricity to the consumers. Though the generation cost to produce electricity has fallen due to the low demand, the transmission and distribution cost remains almost unchanged as the wire costs are almost fixed. Utilities would try to recover the energy costs using various tariffs. Hence, utilities need to keep an eye in the future to increase the energy rate to recover the losses.

- **Supporting the state-owned generation:** It is likely that the maximum of the power generating units are far from the nearest load centre. Generation companies should take appropriate measures now to allocate a proper amount of fuel to ensure the robustness of the supply stream for the next few months. As the demand decreases, a frequency fluctuation situation must be managed very carefully so that it does not go out of control. As previous load forecasting studies could not anticipate this unlikely situation, a new naïve method can be employed. Countries having electric network interconnections with the neighbouring countries should take maximum precautions to keep the generation-demand balance intact. Otherwise, a small mistake may lead to cascading tripping effects, which may lead to a nationwide blackout. If the state is self-sufficient with its energy resource and generation, the regulatory authority should be careful regarding the fuel extraction and electricity export–import at this crucial stage. This helps the overall management of the power supply chain to remain within the respective country's control.
- **Short-term accurate load forecasting:** An accurate load forecasting leads to correct generation scheduling and economic dispatch of generators by an electric utility and thus minimizing the risks to ensure uninterrupted and quality power to the consumers. The unprecedented changes in the demand due to COVID-19 has severe impacts on the accuracy of week-ahead and day-ahead load forecasting. The accuracy of very short-term forecasting in the range of few hours ahead has been found very promising as this mechanism depends on the most recent trends rather than the long-tern seasonality trends. The network operators may also rely on the naïve forecasting mechanism, which would perform better than the long-term predictions [77].
- **Enhancing the cybersecurity of SCADA and other communication infrastructure:** The SCADA system and the communication infrastructure of the power system of a country always have threats from international hackers. If the system has glitches in its communication network and it is found due to an unintentional mistake in the stressed periods of a pandemic, then the whole network may fall prey to the hacker who could pose a national threat. Like many other industries, the utilities also face a shortage of IT experts or cybersecurity experts during the time of such pandemic events. Hence, utilities have to be very prompt, taking actions to safeguard their whole network.
- **Power system maintenance**: Looking at the nationwide daily demand pattern, it is seen that most of the industries and commercial setups are shut down. It is the right time for the utility to intelligently schedule the generation to allow the spare units to carry out much-needed refurbishing and maintenance. The utilities can take this opportunity to inspect the impacts of shutting down a few power plants alternately in a programmed manner. In this way, a utility may identify the efficacy of the emergency power plants.

6.2. Recommendations for the future

Severe unlikely events like COVID-19 may occur in the near future to any country. Hence, responsibilities need to be realized, and steps need to be taken promptly, which would proffer a progressive impact. Until today many utilities and operators have been operating the sector incorporating the conventional mechanisms and styles of management. As the pandemic situation has exposed the severe weaknesses, it is high time policymakers, experts and all stakeholders recognize the integration of modern technologies, mechanisms and managerial styles to be incorporated with the power and energy sector. Some of the recommendations for doing so are as follows:

- **Gradual increase of load**: As the COVID-19 lockdown will be withdrawn, utilities should plan to allow the relaxation of the load to increase step by step to ensure grid stability. Otherwise, tripping may occur due to severe power quality issues. If it is not controlled properly, a weak grid may fall to cascading effects, which would, in turn, create a systemwide blackout.
- **Post-COVID fuel security and supply:** In the post-COVID case, economy would be more inward-looking and deglobalization would occur due to the security of energy and depending on others for all commodities. So, it is the time for policymakers to understand the necessity of fully exploiting their fuel potential before committing to other friendly nations for fuel import/export. An unforeseen regional and global crisis may occur at any time in the near future. Exploring fuel potential also includes assessing the overall renewable energy generation capacity utilizing various types of resources. While the COVID-19 crisis gets over and things become normal again, it would be difficult for the developing countries to compete with the bigger economies for importing fuels, for example, crude oil, LNG, LPG, coal from the international market. Hence, the respective governments should take the necessary steps for exploiting its resources immediately. However, cheap generators could run out of fuel due to excessive usage during global lockdown situation and high-cost generators may have enough fuel. This scenario may increase overall generation costs during the post-COVID maximum demand scenario. Hence, if a country is dependent on fuels imported from another country, it is required to assess the reserve as a pandemic like situation would not give enough time for further procurement within a very short time. There may be disruptions in the fuel supply as well due to the spread of the contaminations on the point of contact between the countries. So, it is the high time countries should think of diversifying the supply or reducing the dependency on foreign resources. Fuel transportation to generation sites is always a big challenge. It is suggested, countries should look after their resources and make sure some power stations are built nearby to the fuel storage facility. It is the regulator's roles, policymakers' role to finally decide on how the country should move ahead to gain fuel security.
- **Support to the renewable sector:** Even though there is a drastic price fall occurred for the crude oil, it would not be justified to withdraw the support to the renewable energy sector. Once the situation overcomes, the oil market would get back to its feet soon. For example, the Indian government has drafted a bill to amend the electricity act to protect renewable energy developers and grow the sector. So, for the time being, it would not be wise not to incentivize the renewable energy sector due to cheaper fuel availability.
- **Investment in renewable energy resource manufacturing:** The renewable energy sector is experiencing slow growth due to the unconsolidated supply chain. Solar PV and wind industries are already seeing logistical delays. The government regulators, policy and decision-makers should carefully evaluate this situation so that development does not get hampered as well as the interest of all parties is served properly in an ethical manner. Auction rules should be flexible enough where developers can commit what they have got now, and the rest can be committed later. Due to the travel ban, it is not possible to get raw materials for renewable energy installations soon and this situation can be considered as a motivation to invest in local manufacturing companies to reinforce supply security. PV systems are considered as the most used distributed renewable energy resource around the world. Hence, considering a manufacturing plant to supply PV systems' accessories would prove to be an asset to a country in the near future.

- **Deployment of solar-based technology**: If the people of rural areas of a country can satisfy their low energy needs using renewable energy resources, that could be a massive benefit to both the rural people and the national utility. This would be a big relief to the utility grid extension burden. During the periods of COVID-19 like events in the future, where any future decision is unknown and people have to stay in their home, being energy self-sufficient is the best way to keep them functioning. For example, in Bangladesh, a total of about 4.13 million Solar Home Systems (SHS) was set up in the rural areas and this small SHS can last long around 7–8 years without creating any severe trouble. On top of that, the solar system price is declining day by day due to the rapid improvement of technology around the world. This long-term initiative, which started almost fifteen years ago, is now helping the people in these areas to keep themselves up to date with the latest information and news regarding the event and take proper measures without delay to keep themselves protected from the adversity of COVID-19. This ensures the rural area's energy security regardless of the fuel price fluctuation worldwide. The use of solar irrigation technology is also recommended as the rural farmer would not have to depend on the vulnerable supply of fossil fuel during a lockdown event. The countries having many off-grid regions may take necessary initiatives to integrate these types of modular systems into their daily lifestyle.
- **Deployment of biogas-based technology**: Biogas is another important source of energy that can fulfil the energy demand of rural areas in many countries around the world. As rural areas usually have small to big dairy farms, it is easier to install a biogas plant there and maintain the daily operation. This source of energy has a high impact on the life of rural women, especially which limits their daily tasks of fuelwood gathering for cooking. On top of that, biogas is a clean resource for cooking which reduces the health hazards of chronic diseases, such as respiratory infections, ailments of the lungs; bronchitis, asthma, lung cancer, and increased severity of coronary artery disease, which are the biggest health threats to a COVID-19 patient [78]. If well-maintained, a rural biogas facility can last for a hundred years, which would eventually help the residents to keep their environment clean.
- **Hydrogen as a future fuel:** Research and innovation can contribute to proposing Hydrogen as one of the alternatives fuels to replace fossil fuel. A greener version of hydrogen can be produced using the renewable resource generated power for electrolysis of water. This would be environment friendly as no CO_2 would be produced in this process. The transportation sector can be highly decarbonized using this technology. In the wake of the Covid-19 crisis, the EU and Germany have indicated their interest in investing in this sector [40].
- **Interest in Nuclear Industry**: As the pandemic situation recovers, the governments try to achieve the UN SDG goals as well as make sure that the energy supply chain remains intact. During the pandemic event, nuclear energy was one of the cleanest and safest energy resources in Europe. There have been lots of talk regarding fossil fuel price and supply. However, power generation from nuclear power plants did not pose any challenges in terms of health risk, contamination risk, fuel supply, emissions and worker safety. Safety measures are already embedded in the nuclear industry, which has been one of the concerning issues due to COVID-19. The World Nuclear Association (WNA) also addressed this issue[40]. This industry will attract more employments to boost up the economy if more large-scale nuclear power plants are planned to be built in future. WNA also projects that nuclear power plant uptake would increase in future
- **Microgrid:** Microgrid is a very well-known concept these days. If bigger urban areas or industrial zone can be clustered and function as microgrids with its generation facilities, that would be the best to handle future power system management during any type of crucial situation. This could also be a new business perspective. During a period of lockdown, consumers in a microgrid environment can produce own energy, sell it to the grid if excess, store the excess energy to use later during the night or cloudy days, monitor real-time energy production, consumption, energy selling and buying price and make a decision to take part into the demand side management mechanism. The consumer can also control the charging and discharging of the vehicle and storage component. In this manner, a self-sufficient consumer can confidently manage his energy necessity according to income and expenditure. Microgrids may exist in institutions, small communities, military bases, commercial and industrial areas. A utility should adopt rules and regulations to allow suburb areas to get off-grid and function as a microgrid if any necessity occurs. Having microgrids within a utility's network bolsters the cybersecurity of the system and improves the well-being and economic advantage of the customers.
- **Tariff restructure to recover financial Loss:** The utilities involved with transmission and distribution network assets would try to recover the loss due to lower load demand. To do this, utilities may increase the tariff as soon as the situation recovers. Hence, regulatory hearings would play an important role in deciding how to divide the cost to recover the deficits.
- **Rebound in the oil price:** There might be chances in the post-COVID period that the current production rate of oil would fall against the demand. This would be due to high demand because of the increased transportation and industrial activities. This means a rebound effect can be expected in the oil and gas sector. However, due to increased interest in renewable energy options, it is unlikely that oil price recovery would slow down the transition. During the post-COVID period, it is important that governments act to re-boost the economy using greener alternatives.
- **Energy efficiency measures:** Besides an immense interest in renewable energy investments, utilities and policymakers put some concentrations on the nationwide energy efficiency programs. Some energy efficiency measures such as fixing the cooling and heating equipment standards, demand-side management programs, promoting green buildings, promoting energy start appliances etc. During any crisis period, more and more people would stay at home and the efficient use of energy would result in well-managed power demand and supply system. These benefits also apply to the new transition of the work pattern as well - work from home (WFH). Deploying energy efficiency measures in the commercial and industrial sectors would make a huge difference in the way energy is utilized now.
- **Building long-term resilience:** COVID-19 pandemic situation has put the power and energy system in a challenging situation and has exposed the vulnerabilities. Responding to these types of incidents with more reliable and safe operation mechanism requires approaches in building resilience in the power and energy sector. Lee and Stout mentioned in a report published by NREL mentioned that, "*Power sector resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions to the power sector*" [79]. The first step to increase resiliency is to make the planning first. This includes long and mid-term planning with a sufficient influx of investment from time to time. Countries should adopt energy resiliency policies to develop an Integrated Resource and Resilience Planning process, which includes capacity expansion, transmission and distribution build-out, considering stakeholders' opinion and interest, several priority interventions, etc. Diversification of the generation resources boosts the resiliency. Integration of various types of distributed generation coupled with storage also boosts the resiliency by supporting off-grid systems or microgrid solutions whoever required.
- **Digitization of the power and energy sector:** From the power and energy sector perspective, a transformation is occurring across the energy value chain, starting from the electricity generation, through transmission and distribution, all the way to the end-use electricity supply for residential, commercial and industrial consumers. In a

large scale, the transformation can be briefly portrayed using three D's - Digitalization, Decarbonization and Decentralization. The transformation applications range from resource performance management, grid optimization and aggregation to integrated customer services [80]. Digitalization is vital for the decentralization of the energy systems. The digital solutions can facilitate the society with reduced GHG emissions, new job opportunities and value for consumers. The transformation triggers a data-driven future by connecting and coordinating data in innovative ways using advanced analytics, Machine Learning, Blockchain, Internet of Things (IoT) and Artificial Intelligence technologies. The blend and assembly of these innovative technologies are the keys to boost the transformation of the power and energy sector. Digital links connect the individual system components which provide a massive amount of valuable data. In this data-driven world, the intelligent combination of artificial intelligence and machine learning would analyze the data that would foster the decision-making and performance of energy generation, transmission and distribution; and the blockchain technology would set up the engine to utilize the data for consumers' energy trading, transparently and robustly. Without the digital infrastructure of the power and energy sector, the concept of Smart Grid would be invalid. A data-driven networked and intelligent multi-storied building can reduce its ecological footprint by as high as 80% [53]. It is essential that during the post-COVID-19 era, the power and energy utilities, operators and all stakeholders recognize the contributions and blessings of these remarkable technologies which would not only transform the entire sector into digital but would facilitate the nations to achieve the United Nation's Sustainable Development Goals (UN SDG) well ahead of time. Therefore, national policymakers should incorporate the digital transformation of the energy sector in their respective country policies to boost up the restructuring of the power and energy sector.

- **Smart Grid:** Smart grid technology is the integration and smart communication between generation system, transmission line, substation, transformers and other systems for reliable service to the consumers. The smart grid is a self-sufficient network system which controls, monitor and analysis complete energy supply system. A smart grid system transmits electricity more efficiently, restores power disturbances quickly and reduces operation and management costs. The complete electric system should adopt smart grid technology for better security of the system and better integration between customer and utility sector. This technology would also lead to better utilization of renewable energy sources. Smart grid recognizes the blessings of the blending of the digitalization of the sector, distributed integration of renewable energy resources, presence of energy market and implementation of microgrid infrastructures. The exposed vulnerabilities of the energy sector can be well addressed by fully utilizing the capabilities of Smart Grid in the respective countries.
- **Demand-side load management:** Demand side load management strategy reduces investment cost in the power generation and transmission sector in order to meet the peak load demand. Demand-side management also allows grid operators to balance intermittent electricity generation from solar and wind plants, which give a boost to renewable energy sources. The demand-side load management activity attempts to balance electricity generation and demand closer to perceived optimum, giving benefit to both consumer and energy providers. National investment in generation and transmission sector can be well deferred to a later time due to well-planned demand-side load management programs.
- **National Policy:** After the pandemic situation recovers, it is desired to decide on how much the country needs to generate to accelerate the future economy. This would eventually decide if the country needs to move to more generations either from thermal power or green energy sources. To build a new thermal power plant, a good number of skilled people are required, but for renewable energy plants more diversified and generalized background people can work, but their total numbers could be less compared to the other case. This would have an impact on the job sector, as well. The government needs to consider various other issues to boost up the power sector-oriented economy. The country policy would decide if a foreign investor should be allowed to invest or not. It has both pros and cons for any country. In that case, it is required to check what are the rules for the lenders who would lend the money to the investors. There could also be a debate on whether the investment should be in the power generation sector or in the grid or maybe on the virtual power plants, demand-side managements, or perhaps more corrective market where consumers become prosumers. A report published by NREL mentioned that Vietnam plans to launch a wholesale electricity market by 2023, and in Thailand, a dialogue is emerging over whether the government can continue to support a state-owned single-buyer utility in the wake of their recent expenditures [47]. All these new projects and ideas would depend on the respective government policies and regulatory environment of the country. Investment in new technologies can enable greater power system controllability, but cost-benefit analysis must be understood.

7. Conclusions

The COVID-19 Pandemic pandemic has had a profound effect on public health, economic and social impacts and affected all aspects of life, including the power sectors around the world. The nation and/or region-wise lockdown imposed to reduce the COVID-19 has affected the operation of businesses, industries and transportation, which resulted in a change in electric load demand pattern. Due to the changes in work patterns and lifestyle, residential electricity demand has increased while industrial/commercial load demand has reduced and eventually has affected the national energy demand profile. Optimum operation and maintenance of the power system become critical due to these load changes and hence, utilities around the world are taking many initiatives to tackle these challenges to ensure a smooth operation of the power system. This study has investigated the direct impacts that occurred during the pandemic in the power system such as power demand variation including technical and economic issues associated, while the indirect impact that eventually influences the power sector operation such as the implementation of new projects, investments etc. From the preliminary analyses, it has been evident that commercial load demand was dropped maximum while residential load demand was increased maximum during the lockdown. The study then investigated various issues and challenges faced by the utilities in the Indian power system, including the essential measures taken to retain the grid frequency and voltage profile within their recommended band. From the analyses, it is evident that Indian utilities managed this challenging situation efficiently without much interruption into the power systems network, including the nine-minute light-off event. Finally, the lessons learned from the Indian utilities as well as based on the existing researches, knowledge-based and personal experience, this study proposed a set of recommendations for a smooth operation of the power system globally during this pandemic condition. Recommendations are also proposed to gradually overcome this crisis as well as for a sustainable operation of the power systems in the near future. This study will be useful for the government, policymakers, utilities and stakeholders around the world to handle this pandemic crisis as well as a pandemic alike scenario in the near future.

CRediT authorship contribution statement

Rajvikram Madurai Elavarasan: Conceptualization, Methodology, Visualization, Data curation, Formal analysis, Investigation, Writing, Reviewing. **GM Shafiullah:** Conceptualization, Methodology, Formal analysis, Investigation, Writing, Reviewing, Supervision. **Kannadasan Raju:** Investigation, Analysis, Writing. **Vijay Mudgal:** Investigation, Analysis, Writing. **M. T. Arif:** Data Curation, Investigation, Analysis, Writing. **Taskin Jamal:** Conceptualization, Methodology, Writing, Reviewing. **Senthilkumar Subramanian:** Data Curation, Analysis. **V.S. Sriraja Balaguru:** Data Curation, Analysis. **K.S. Reddy:** Reviewing. **Umashankar Subramaniam:** Reviewing.

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.

Acknowledgement

The authors acknowledge the support provided by the Power System Operation Corporation (POSOCO), State Load Despatch Centre (SLDC), India in providing the sufficient power grid generation and demand data for carrying out the analysis of the proposed work.The authors also acknowledge the Australian Energy Market Operator's (AEMO) online data repository as a data source for the Australian power network load data. The authors thank Mr.Rishi Pugazhendhi, Department of Mechanical Engineering, Sri Venkateswara College of Engineering, Chennai, India for having helped with some valuable inputs during the revision stage of the work. We also thank Dr. J. Balamurugan, Assistant Execution Engineer, Commercial, TANGEDCO, who has helped in cumulatively collecting and sharing the issues and challenges faced by the Indian grid operators during COVID-19 period. Recommendations suggested by the engineers working in SLDC to overcome the power grid issues during the pandemic is gratefully acknowledged.

References

[1] Jarus O. "20 of the worst epidemics and pandemics in history, Live Science, March 20, 2020." https://www.livescience.com/worst-epidemics-and-pandemics-in-history.html (accessed April 26, 2020).
[2] Hickok K. "What is a pandemic? March 13, 2020." https://www.livescience.com/pandemic.html (accessed April 26, 2020).
[3] Worldometers. "Coronavirus Cases: COVID-19 Coronavirus Pandemic." https://www.worldometers.info/coronavirus/#countries (accessed April 20, 2020).
[4] Madurai Elavarasan R, Pugazhendhi R. Restructured society and environment: A review on potential technological strategies to control the COVID-19 pandemic. 138858 Sci Total Environ 2020/07/10/ 2020;725. https://doi.org/10.1016/j.scitotenv.2020.138858.
[5] Chintalapudi N, Battineni G, Amenta F. COVID-19 virus outbreak forecasting of registered and recovered cases after sixty day lockdown in Italy: A data driven model approach. 2020/04/13/ J Microbiol Immunol Infect 2020. https://doi.org/10.1016/j.jmii.2020.04.004.
[6] Barkur G, Vibha, Kamath GB. "Sentiment analysis of nationwide lockdown due to COVID 19 outbreak: Evidence from India," (in eng). 102089–102089 Asian J Psychiatry 2020;51. https://doi.org/10.1016/j.ajp.2020.102089.
[7] Chatterjee K, Chatterjee K, Kumar A, Shankar S. Healthcare impact of COVID-19 epidemic in India: A stochastic mathematical model. 2020/04/02/ Med J Armed Forces India 2020. https://doi.org/10.1016/j.mjafi.2020.03.022.
[8] Zambrano-Monserrate MA, Ruano MA, Sanchez-Alcalde L. Indirect effects of COVID-19 on the environment. 2020/08/01/ Sci Total Environ 2020;728:138813. https://doi.org/10.1016/j.scitotenv.2020.138813.
[9] Cao W, et al. The psychological impact of the COVID-19 epidemic on college students in China. 112934 Psychiatry Res 2020/05/01/ 2020;287. https://doi.org/10.1016/j.psychres.2020.112934.
[10] Francis NN, Pegg S. Socially distanced school-based nutrition program under COVID 19 in the rural Niger Delta. The Extractive Industries and Society 2020/04/21/ 2020. https://doi.org/10.1016/j.exis.2020.04.007.
[11] Haleem A, Javaid M, Vaishya R. Effects of COVID 19 pandemic in daily life, (in eng). Curr Med Res Pract, p. 10.1016/j.cmrp.2020.03.011, 2020, doi: 10.1016/j.cmrp.2020.03.011.
[12] CNBC. "World Markets." https://www.cnbc.com/world-markets/ (accessed April 20, 2020).
[13] Kabir M, Afzal MS, Khan A, Ahmed H. COVID-19 pandemic and economic cost; impact on forcibly displaced people, (in eng). 101661–101661 Travel Med Infect Dis 2020. https://doi.org/10.1016/j.tmaid.2020.101661.
[14] AEMO. Australian energy market operator, quarterly energy dynamics Q1 2020, market insights and WA market operations. AEMO. https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q1-2020.pdf?la=en&hash=490D1E0CA7A21DB537741C5C18F2FF0A (accessed April 25, 2020).
[15] UNESCO. COVID-19 educational disruption and response. https://en.unesco.org/covid19/educationresponse (accessed April 22, 2020).
[16] Jin H, Lu L, Liu J, Cui M. Complex emergencies of COVID-19: management and experience in Zhuhai, China. Int J Antimicrobial Agents, p. 105961, 2020/03/28/ 2020, doi: https://doi.org/10.1016/j.ijantimicag.2020.105961.
[17] Lau H, et al. Internationally lost COVID-19 cases. J Microbiol Immunol Infect 2020/03/14/ 2020. https://doi.org/10.1016/j.jmii.2020.03.013.
[18] The American Journal of Emergency Medicine. Wilderness & Environmental Medicine, vol. 23, no. 1, p. 89, 2012, doi: 10.1016/j.wem.2011.11.003.
[19] Roy D, Tripathy S, Kar SK, Sharma N, Verma SK, Kaushal V. Study of knowledge, attitude, anxiety & perceived mental healthcare need in Indian population during COVID-19 pandemic. 102083 Asian J Psychiatry 2020/06/01/ 2020;51. https://doi.org/10.1016/j.ajp.2020.102083.
[20] Rajkumar RP. COVID-19 and mental health: A review of the existing literature. 102066 Asian J Psychiatry 2020/08/01/ 2020;52. https://doi.org/10.1016/j.ajp.2020.102066.
[21] Zhang D, Hu M, Ji Q. Financial markets under the global pandemic of COVID-19. Finance Res Lett 2020;101528. https://doi.org/10.1016/j.frl.2020.101528. 2020/04/16/.
[22] Gallego V, Nishiura H, Sah R, Rodriguez-Morales AJ. The COVID-19 outbreak and implications for the Tokyo 2020 Summer Olympic Games (in eng). 101604–101604 Travel Med Infect Dis 2020. https://doi.org/10.1016/j.tmaid.2020.101604.
[23] Holmes EA, et al. Multidisciplinary research priorities for the COVID-19 pandemic: a call for action for mental health science. 2020/04/15/ The Lancet Psychiatry 2020. https://doi.org/10.1016/S2215-0366(20)30168-1.
[24] Batsas M. Public transport authorities and COVID-19, impact and response to a pandemic. International Association of Public Transport, Australia/New Zealand. https://australia-newzealand.uitp.org/sites/default/files/V1_COVID-19%20impacts_AJ_v03.pdf (accessed May 17, 2020).
[25] BBC. BBC Report, Coronavirus: A visual guide to the economic impact. https://www.bbc.com/news/business-51706225 (accessed April 27, 2020).
[26] Tuohy A, Kelly A, Deaver B, Lannoye E, Brooks Daniel. Aidan Tuohy, Adrian Kelly, Brian Deaver, Eamonn Lannoye, Daniel Brooks, COVID-19 Bulk System Impacts, Demand Impacts and Operational and Control Center Pactices, EPRI Transmission Opearions and Planning, ID: 3002018602. http://mydocs.epri.com/docs/public/covid19/3002018602R2.pdf (accessed April 25, 2020).
[27] IEA. Data and statistics, Explore energy data by category, indicator, country or region, https://www.iea.org/data-and-statistics?country=AUSTRALI&fuel=Energy%20consumption&indicator=Carbon%20intensity%20of%20industry%20energy%20consumption (accessed June 20, 2020).
[28] Load data of New York city, USA. http://mis.nyiso.com/public/P-58Blist.htm (accessed Arif 25, 2020).
[29] AEMO. Australian Energy Market Operator Network Load data, Australia. http://www.nemweb.com.au/REPORTS/CURRENT/HistDemand/ (accessed April 25, 2020).
[30] Commercial down v residential up: COVID-19's electricity impact, 2020 Energy Insider, Energy Networks Australia. https://www.energynetworks.com.au/news/energy-insider/2020-energy-insider/commercial-down-v-residential-up-covid-19s-electricity-impact/ (accessed April 19, 2020).
[31] Indian Energy Exchange. https://www.iexindia.com/marketdata/market_snapshot.aspx (accessed April 18, 2020).
[32] COVID-19: America hasn't used this little energy in 16 years, World Economic Forum. https://www.weforum.org/agenda/2020/04/united-states-energey-electricity-power-coronavirus-covid19/ (accessed April 19, 2020).
[33] Fall in demand and prices of the European electricity markets due to the COVID 19 crisis, AleaSoft Energy Forecasting. https://aleasoft.com/fall-demand-prices-european-electricity-markets-due-covid-19-crisis/ (accessed April 19, 2020).
[34] Here's how energy demand has changed during the UK's lockdown, World Economic Forum. https://www.weforum.org/agenda/2020/04/we-analysed-electricity-demand-and-found-coronavirus-has-turned-weekdays-into-weekends/ (accessed April 19, 2020).
[35] Yep E, Odaka M, Kanoi S, Kumagi T. Japan, Singapore lockdowns to stifle Asian gas, power demand further, COVID-19: Coronavirus outbreak, S&P Global Platts. https://www.spglobal.com/platts/en/market-insights/latest-news/natural-gas/040720-japan-singapore-lockdowns-to-stifle-asian-gas-power-demand-further (accessed April 19, 2020).
[36] Abdi B. Coronavirus impact: Within ten days, 26 per cent fall in India's energy consumption, ET Energy World. https://energy.economictimes.indiatimes.com/news/power/coronavirus-impact-within-ten-days-26-per-cent-fall-in-indias-energy-consumption/74854825 (accessed April 19, 2020).
[37] Postelwait J. China's electricity demand dropped almost 8% after COVID-19 Measures, T&D World. https://www.tdworld.com/electric-utility-operations/article/21127472/chinas-electricity-demand-dropped-almost-8-after-covid19-measures (accessed.
[38] European power exchange (EPEX SPOT) SE. https://www.epexspot.com/en (accessed April 19, 2020).

[39] The Iberian electricity market. https://www.mibel.com/en/home_en/ (accessed April 19, 2020).
[40] McGrath M. Five key questions about energy after Covid-19. https://www.bbc.com/news/science-environment-52943037 (accessed June 27, 2020).
[41] AEMO. Latest COVID19 demand impact summary. https://aemo.com.au/en/news/latest-covid19-demand-impact-summary (accessed June 20, 2020).
[42] C.R. Service. COVID-19: potential impacts on the electric power sector. https://crsreports.congress.gov/Content/html/covid19.html (accessed June 20, 2020).
[43] Energy.gov.au. Government responses to COVID-19 in the energy sector, Australian Government. https://www.energy.gov.au/energy-sector-response-novel-coronavirus-covid-19/government-responses-covid-19-energy-sector (accessed June 21, 2020).
[44] IEA. COVID-19, An unprecedented global health and economic crisis. https://www.iea.org/topics/covid-19 (accessed June 21, 2020).
[45] Birol F. The coronavirus crisis reminds us that electricity is more indispensable than ever, IEA. https://www.iea.org/commentaries/the-coronavirus-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever (accessed June 20, 2020).
[46] IRENA. COVID-19 and renewables - impact on the energy system, international renewable energy agency. https://www.irena.org/events/2020/Jun/COVID-19-and-renewables—impact-on-the-energy-system (accessed June 20, 2020).
[47] Lowder T, Lee N, Leisch JE. COVID-19 and the power sector in southeast Asia: Impacts and opportunities, usaid, nrel. AIG-19-2115, June 2020 2020. [Online]. Available: https://www.nrel.gov/docs/fy20osti/76963.pdf.
[48] PVmagazine. Impact of Covid-19 on the global energy sector. PV magazine. https://www.pv-magazine-australia.com/2020/04/28/impact-of-covid-19-on-the-global-energy-sector/ (accessed June 20, 2020).
[49] Camera FL. Staying on course: renewable energy in the time of COVID-19. International renewable energy agency (IRENA). https://www.irena.org/newsroom/pressreleases/2020/Apr/Staying-on-Course-Renewable-Energy-in-the-time-of-COVID19 (accessed June 19, 2020).
[50] IRENA. Call to action in response to COVID-19: Renewable energy is a key part of the solution. https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/Publication/IRENA_Coalition_COVID-19_response.pdf (accessed June 20, 2020).
[51] IEA. Covid-19 impact on electricity. https://www.iea.org/reports/covid-19-impact-on-electricity (accessed June 21, 2020).
[52] Eurelectric. Impact of COVID-19 on the electricity value chain, eurelectric recommendations, electric powering people. https://cdn.eurelectric.org/media/4498/recommendations_-_impact_of_covid-19-2020-030-0400-01-e-h-327DEFF7.pdf (accessed.
[53] Massei CV. COVID-19 will accelerate the revolution in energy systems, World Economic Forum. https://www.weforum.org/agenda/2020/05/covid-19-accelerate-energy-revolution/ (accessed June 21, 2020).
[54] Cohn L. COVID-19 providing a world of research on the grid and microgrids: IEEE. https://microgridknowledge.com/microgrids-covid-19-ieee/ (accessed June 21, 2020).
[55] World Population by Country. https://www.worldometers.info/world-population/ (accessed April 17, 2020).
[56] BP. BP statistical review of world energy 2019. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf (accessed april 17, 2020).
[57] Euroelectric. Impact of COVID-19 on customers and society, recommendations from the european power sector. https://cdn.eurelectric.org/media/4313/impact_of_covid_19_on_customers_and_society-2020-030-0216-01-e-h-E7E407BA.pdf (accessed April 21, 2020).
[58] Our energy story. Energy market authority, smart energy sustainable future, Singapore Government. https://www.ema.gov.sg/index.aspx (accessed April 21, 2020).
[59] Global coal generation fell by a record amount in 2019, while COVID-19 may cause bigger fall in 2020, PV Magazine. https://www.pv-magazine-australia.com/2020/04/02/global-coal-generation-fell-by-a-record-amount-in-2019-while-covid-19-may-cause-bigger-fall-in-2020/ (accessed April 21, 2020).
[60] Enedis -France. Enedis 2020. https://www.enedis.fr/english (accessed April 21, 2020).
[61] Renewables achieve clean energy record as COVID-19 hits demand, Renew Energy World. https://www.renewableenergyworld.com/2020/04/06/renewables-achieve-clean-energy-record-as-covid-19-hits-demand/ (accessed April 21, 2020).
[62] Government of India, Ministry of Power. https://powermin.nic.in/en/content/power-sector-glance-all-india (accessed April 18, 2020).
[63] Power system operation corporation (POSOCO) limited, National Load Despatch Centre, India. https://posoco.in/ (accessed April 27, 2020).
[64] TheIndianExpress. "Only 30% of power is used for house lights, so switching them off shouldn't trip the grid… we hope." The Indian Express. https://indianexpress.com/article/explained/sunday-9-pm-lights-out-india-electricity-grid-impact-explained-6346980/ (accessed April 29, 2020).
[65] MapsofIndia. "India, Power Grid Regions." https://www.mapsofindia.com/maps/india/power-grid.html (accessed April 30, 2020).
[66] UN. India plans to produce 175 GW of renewable energy by 2022, Sustainable Development Goals. https://sustainabledevelopment.un.org/partnership/?p=34566#:~:text=The%20Government%20of%20India%20has,GW%20from%20small%20hydro%2Dpower (accessed June 18, 2020).
[67] Growth of Electricity sector in India from 1947-2019 - by Central Electricity Authority, Minsirty of power, Government of India. http://cea.nic.in/dailygeneration.html (accessed April 17, 2020).
[68] National Power Portal, India. https://npp.gov.in/publishedReports# (accessed April 17, 2020).
[69] DERC. Electricity Tariff For FY 2019-20, Delhi Electricity Regulatory Commission, http://www.derc.gov.in/Press%20Release/Press%20Release%2031.07.2019/Press%20release.pdf (accessed April 17, 2020).
[70] Discoms to suffer Rs 30K cr revenue loss, face Rs 50K cr liquidity crunch due to lockdown: CII, ET Energy World. https://energy.economictimes.indiatimes.com/news/power/discoms-to-suffer-rs-30k-cr-revenue-loss-face-rs-50k-cr-liquidity-crunch-due-to-lockdown-cii/75197169 (accessed April 19, 2020).
[71] India imported solar power equipment worth $1,180 mn from China in Apr-Dec FY20, ET Energy World. https://energy.economictimes.indiatimes.com/news/renewable/india-imported-solar-power-equipment-worth-1180-mn-from-china-in-apr-dec-fy20/74493914 (accessed April 19, 2020).
[72] Sasi A. Solar imports soar, it's now more make-in-China than make-in-India. The Indian Express. https://indianexpress.com/article/business/solar-imports-soar-its-now-more-make-in-china-than-make-in-india-6222146/ (accessed April 19, 2020).
[73] Simonovich L. Why COVID-19 is making utilities more vulnerable to cyberattack - and what to do about it. World Economic Forum. https://www.weforum.org/agenda/2020/04/why-covid-19-is-making-utilities-more-vulnerable-to-cyberattack-and-what-to-do-about-it/ (accessed July 28, 2020).
[74] ISOConsultingServices. ISO 27001: 2013 – Information Security Management System (ISMS), What is ISO 27001?. https://www.isoconsultingservices.com.au/iso-27001-2013-information-security-management-system-isms/?gclid=Cj0KCQjwvIT5BRCqARIsAAwwD-SsyKLzq2346jmDQuBqBgDgW2hDGsQm2sdLlqOQ-JYMmYoe0prPpiEaAsY9EALw_wcB (accessed July 28, 2020).
[75] EnergyQuest. Providing timely data, rigorous analysis and sound strategic advice on Australian energy. https://www.energyquest.com.au/energyquarterly-march-2020/ (accessed April 26, 2020).
[76] Haider SZ, Haider S. Challenges for electric utilities amid COVID-19. Energy and power. https://ep-bd.com/view/details/article/NDcyMg%3D%3D/title?q=challenges+for+electric+utilities+amid+covid-19 (accessed April 25, 2020).
[77] Alt M. Impact of COVID-19 related shutdowns on utility-scale electric demand and forecasting: an indian metropolis use case. https://www.bluwave-ai.com/impact-of-covid-19-shutdowns (accessed April 27, 2020).
[78] The importance of biogas to a big city and rural villages. https://blog.anaerobic-digestion.com/importance-of-biogas-big-city-rural-villages/ (accessed April 29, 2020).
[79] Leisch JE. Planning a resilient power sector, resilient energy platform. https://www.nrel.gov/docs/fy19osti/73618.pdf (accessed June 21, 2020).
[80] Chebbo M. https://www.ge.com/renewableenergy/sites/default/files/related_documents/GE_Digital_Transformation.PDF (accessed June 10, 2020).