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The progress, impact analysis, challenges and new perceptions for electric power and energy sectors in the light of the COVID-19 pandemic

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1. Introduction

1.1. Background: Impact of COVID-19 on the power system and energy demand

The big electrical energy customers are forced to minimize or shut their operations owing to the precautionary COVID-19 pandemic guidelines. Residential energy consumption increases as a result of restrictions on people to stay at home [1]. This change in living and working approach results in a considerable variation in load profile constituents and electrical demand levels during different periods. The operation and control of the power system have been affected by the change of load pattern [2]. Electricity energy demand and its typical load pattern are often affected by internal and external factors that the power generation system responds accordingly through grid operators [3]. Due to the execution of lockdown restrictions worldwide, electricity demand has significantly dropped, while the daily energy utilization and load nature have also changed [4]. The uncertain variations in electrical demand have posed stress on load-serving entities and power system maintenance. Lockdown measures that avoid the spread of the pandemic have given rise to sudden changes in socioeconomic habits, which cause direct impacts on the power systems [5]. With the fast implementation of the precautionary COVID-19 guidelines and the unusual spread of the pandemic, the power system management and control also confront a higher degree of ambiguity. Along with the technical constraints, the environmental and financial traits of the electrical energy sector are also affected. With the decreasing electricity demand and the boosting percentage of renewable energy sources (RESs) generation during the pandemic, reduced gaseous emissions and a decrease in electricity price have been instantaneously noticed [6].

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On the other hand, building energy demand has gradually increased over since the past 50 years, so enhancing the energy performance of buildings has significant attention [7]. To lessen dependence on fossil fuels and CO₂ emissions, the net-zero energy consumption concepts is considered for buildings with collecting energy on-site by way of environmentally-friendly technologies such as using highly efficient heating, ventilation and air conditioning and solar systems [8]. However, the development of more efficient and widespread smart cities is responding to the ongoing COVID-19 outbreak in some critical ways from the increasing use of public energy data to monitoring traffic [9]. The integration of the RES, battery storage, electric vehicles (EVs) and vehicle-to-grid into smart cities provides important solutions. Renewable energy sectors having sustainability and economic development need an analysis of factors that encourage the efficiency and the social effects for smart cities development [10]. With the promotion of regionalized or distributed renewable energy generation and smart energy management policies, the transition to sustainable and effective energy systems is accelerated [11].

1.2. Background: economy, social area and oil price

The economy of any country is primarily dependent upon energy. Economy, business, growth, development and energy are mainly reliant on public need and ability [12]. Community protection and health are the main consideration to meet people demands as well as development. The development has disrupted many times during disease eruption for instance; Plague of Athens in 430BCE, Circa of China in 3000BCE, to the most recent Zika Virus outbreak in 2015. All these pandemics cause thousands of casualties. The first quarter of the year 2020 is unfathomable to notice worldwide lockdown as a result of a new virus occurrence. WHO (World Health Organization) announced it as a virulent disease on 12th March 2020 [13]. This virus is propagating all over the world and the most influenced countries are Italy, Iran, Spain, mainland China, France, United Kingdom (UK), Germany, and the USA. The global death toll has risen to 203,000, 0 as of 19th January 2021 [14].

Due to the non-availability of medicine, social distancing, use of the mask is the best attempt to reduce the spreading of the pandemic. Therefore, the different states announced national level lockdown and people were not permitted to exit from their homes [15]. The social restrictions, lockdown, joblessness, travel ban and working from home compelled most of the individuals to remain at home, which altered the usual business and declined energy demand from the national grid. Business shrunk their function, small businesses nearly ceased, industries stopped their manual operations, travel ban almost downfall the aviation activity, academics shifted to virtual form and most other sectors implemented the policy to work from home [16]. The worldwide market is significantly influenced by these movements and raises job loss and neediness [17]. Besides, the COVID-19 pandemic has affected the economic and social sections of all the countries in the following areas [18].

- The international oil price has reduced to the lowest since 2003 owing to a reduction in energy demand during the COVID-19 pandemic [19]. It causes business issues, unemployment and power system uncertainties in Middle East countries and Russia [20].
- More than 91% of registered students worldwide are affected by the closure of academic institutes [21]. However, several institutes have shifted to the online system that causes an increase in energy consumption of the residential sector.
- Industrial operation and business slowed down and the stock market diminished to 25% during the pandemic that also affects the power system [22].
- The transportation sector especially the aviation sector is badly affected. Most of the airports have curtailed their flight operations and cause an uncertain reduction in electrical demand.
- The use of public transport is reduced to 80 to 90% in several countries. Most of the countries have public transportation systems dependent on electricity thus; there is a huge impact on power systems [23].
- Most of the countries and research institutes put efforts and investments into the fight against COVID-19 [24]. There is a possibility of delay or stoppage of different distributed energy resources (DERs) related initiatives. However, it has brought forward new research areas in emergency medical management, disaster management, and power system management to tackle these uncertainties [25].

A secure power system is the main necessity of a functioning society. Since most people are forced to work from home during
COVID-19, an uninterrupted power supply has a vital role. On the one hand, the internet is the main requirement during these unforeseen times when continual electricity is mandatory. The reliability of the power system is mainly dependent upon demand and generation variations. Administrations and power industries should take preventive actions so that they can confront the challenges and issues observed for efficient procedure. The energy sectors should be restructured that can be handled to a forthcoming unanticipated pandemic like circumstances. Substantial uncertainties in the system perform it inconvenient to protect a demand–supply balance for power system operators [26].

1.3. Literature review

The pandemic has severe impacts on all sectors, but the electrical power sector is adversely affected [27]. Energy is consumed to a greater extent in the commercial, industrial and residential energy sectors depending upon the region [28]. The residential energy consumption increases with restrictions as people stay at home. Change in living and working approach results in a considerable variation in load profile constituents and electrical demand levels during different periods [29]. Transition consumption profile further influences the power system control and operation. It also may adversely influence the utility grid types of equipment such as distribution transformers, protection devices and substations. Furthermore, it could have a severe effect on the national power grid if it were not controlled appropriately by the electric utility [30]. Several studies evaluate the impact of the pandemic on the environment, air quality, economy and power & energy sectors. Jia et al. [31] have discussed the impacts and reacts of the pandemic and oil price on energy, environment and economy. Authors in [1] have investigated and analysed the potential impacts on the power system during COVID-19 pandemic together with the technical and socio-economic challenges facing the utilities. Jiang et al. [32] have outlined the global effects of the COVID-19 on the energy demand and consumption and discussed energy related with lessons, challenges, and emerging opportunities. Authors in [33] have addressed effects of COVID-19 on the power systems and market operations. Wang et al. [34] have investigated that the lockdown measures have an outstanding effect on air quality. The COVID-19 provides to reduce CO₂ emissions and to get a better air quality. Authors in [35] analyses the lockdown measures on the electric energy use of municipal buildings during COVID-19. Another interesting study is that resilient renewable energy supply network is discussed regarding demand, supply and payment risks as a result of COVID-19 [36]. Authors in [37,38] have assessed COVID-19 pandemic from energy, environmental, sustainability and climate change perspectives. In [39], the impact of COVID 19 on power system operations based upon data from SaskPower Corporation in Canada has been investigated. However, the main focus of Ref. [39] is SaskPower Corporation in Canada, but the proposed paper has provided an analysis of the impacts of the COVID 19 in the context of different power system parameters around the world and especially New York City (NYC). In this paper, the HDDs and CDDs are also analysed to observe the impacts on heating and cooling demand. Besides, average values of the CDDs and HDDs from 2016 to 2020 with varying base temperature in NYC has been discussed in detail. In [40], there is an energy outlook, but there is no deep analysis related to power system operations and uncertainties in the context of the COVID-19.

The aforementioned studies have provided different sights to understand the effects of the COVID-19 pandemic. However, the COVID-19-related studies are still inadequate for the following reasons: (i) critical factors affecting the development of the REP before, during and after COVID-19 pandemic, (ii) lack of comparison for estimation of energy demand based on cooling degree days (CDDs) and heating degree days (HDDs) methods with the same period in prior years around the world, (iii) the impact of climate change on energy demand, (iv) investigating the impact of utilization of new efficient technologies, temperate weather and economic growth on the energy efficiency/energy intensity, energy demand and energy usage and (v) the impact of COVID-19 on the power system operation. Some of the literature’s results are required to be further addressed as mentioned above. Therefore, the aggregate impacts of the COVID-19 pandemic are aimed to fill the knowledge gap with this paper in the context of electric power and energy sectors.

1.4. Key contributions and paper organization

This paper presents detailed analyses based on the development of the renewable energy technologies (RETs), electric power and energy statistical data, challenges and new perceptions for power system operation for before, after, and during the COVID-19 outbreak. The impacts and challenges of the COVID-19 on electric power and energy sectors have been mainly addressed in three aspects: power system operation issues, critical factors affecting the REP and electric energy demand. Statical information about the effects of pandemic implications on the electrical energy system is also examined to help researchers and academicians better understand. Furthermore, this study can provide a direction in opening new avenues to promote energy saving and to boost energy efficiency. In this paper, the impacts of the pandemic on the electrical energy system are described in the following aspects, specifically;

- The increased usage of the RESs during lockdown restrictions of COVID-19 are discussed in detail.
- The important factors influencing the development of renewable energy production (REP), for instance, electric demand, electric markets, economy and environment, have been studied during the COVID-19 outbreak.
- The diminishing of electrical demand in the industrial, transportation, and business sectors is examined and the increase in energy consumption in the residential sector is investigated.
- Estimation of energy demand has been conducted based on the CDDs and HDDs methods to observe electricity consumption.
- The issues faced by utilities related to power system maintenance because of increased RESs and decreased electric demand is also addressed.
- The changes and pressures in daily load profiles and load composition have been observed on the power system operators.
- The impact of the pandemic has been examined for ongoing investment projects/investment plans.
- Impact of the weather conditions, partial lockdown and full lockdown measures taken by the countries on the electricity demand are investigated and analysed before and during the COVID-19 pandemic.
- The energy efficiency or energy intensity and climate change related to the energy demand has been investigated and analysed during the pandemic.

The organization of the present study is arranged as follows: After overviewing a detailed survey of implications of the COVID-19 on the electric energy sector in Introduction Section, Section 2, the impacts of the COVID-19 outbreak on power system operation are investigated. Section 3 provides an overview of REP technologies and factors affecting the development of renewable energy sectors and/or markets in general and during the pandemic. In Section 4, various implications are discussed to describe...
variations in electric demand and for the electrification of the transport sector during COVID-19. Finally, the presented study along with the future recommendations is provided in Section 5. The abbreviations in the paper is listed in Nomenclature Table to provide better understand the study.

2. Power system operation issues during COVID-19

Changing consumption patterns, along with the effect on peak demand and energy consumption, conducts several challenges for system and operators utilities [41]. The power system reliability and electricity market has been affected by demand reduction [42]. While the COVID-19 crisis has revealed some vulnerability in power systems, it also provides a chance to maintain flexible energy sector planning and sustainable and reliable energy [32]. The reliability of the electrical networks system is dependent more on the changeability and nature of electricity demand and generation than on the total energy consumption. Major changes in electricity demand result in greater difficulties for electric grid operators to continue demand-supply balance, particularly at high estimation error levels [43]. The decrease in energy consumption, the changes in load profiles and load composition during COVID-19 bring challenges for the power system operation owing to varying lockdown policies in different regions [44]. Therefore, the minimum stable values of the generation should be determined to operate the power system as reliably and economically [45].

Power system stability is the capability of a power system to recover its steadiness state after being exposed to any disruption [1]. The disorders could be load variations, generator or line outages, faults, voltage downfall or some blend of these. Situation of the power system before and during COVID-19 is shown in Fig. 1 [1]. The power system operation has been observed and analysed under a period of normal conditions (before COVID-19 pandemic) and pandemic (throughout COVID-19) as can be seen in Fig. 1. In general, power system stability is categorized in 2004 by IEEE CIGRE as frequency, rotor angle and voltage stability as depicted in left of Fig. 2. Besides, some extended classifications such as resonance and converter-driven stabilities in 2020 recommended by IEEE are investigated (see right of Fig. 2) [46]. Each of these three stabilities can be further than classed into large, small or large disturbance, long term or short term [47]. The division of the power system stability is portrayed in Fig. 2. The main issues faced by power systems related to power system stability during COVID-19 are detailed in subsections.

2.1. Power system management and maintenance issues

The COVID-19 pandemic creates management and maintenance issues for the power system. The lockdown activities, traffic restrictions and interruption of the supply chain constitute challenges for generators and grid maintenance. Periodic maintenance actions are generally planned for years. However, these works are reasonably suspended or even abandoned during the COVID-19 period. Maintenance works for power plants were suspended to prevent the threat of the COVID-19 for employees in some states of the USA [48]. In Australia and New Zealand, intended outages for maintenance works were suspended, only ones that were vital to the security operation of the system were progressed [49]. The planned maintenance and refilling are accomplished under a strict authority to evade the blowout of the virus for nuclear power plants, of which nuclear reactors must be resupplied every 19 to 24 months [50].

As for the efficient system operation dispatchers and other workers are very important in the power system control and dispatch centres. The strictest COVID-19 protective actions have been taken in dispatch centres of the power system in several countries like the USA, China and India that are affected by the pandemic. The managers and dispatchers have been isolated from outside in China and backup personals have prepared for necessary actions. The Electric Power Research Institute (EPRI) in the USA reviews the operational policies by utilities during the pandemic in the USA as portrayed in [59]. The utilities have executed rotate duty scheme, using backup control centres, applying strict disinfecting and cleaning activities to avoid the influence of the virus. The remote control for some distribution systems below 100 kV such as outage management system (OMS), supervisory control and data acquisition (SCADA) and distribution management system (DMS) were permitted, which facilitated employees to operate from home. As the online working and cloud meetings become extensively recognized during the COVID-19, the pandemic also sheds light on novel practices in the operation and management of power system management such as no-operator substation, Al-supported dispatch system and operation strategy for a power system with high-level resilience. The COVID-19 impacts on power systems for different locations are summarized in Table 1.

2.2. Tackling power balance with uncertainties in electric energy demand

The higher peak-to-valley difference is observed by the higher consumption of the daily residential load during COVID-19. The increased distributed PV penetration intensifies the condition and makes the load profile a “duck curve” with an extended neck and shorter belly [60]. Therefore, thermal units must be gone out of business at midnight to evade excessive generation, and more gas units must be executed to afford ramping flexibilities. Some emergent flexible resources, such as energy storage and demand-side management (DSM), are emphasized and discussed in [61]. The power balance is also challenged by uncertainties evolving from both the generation and demand side [62]. The balance of power system can be provided through a multistage generation scheduling procedure, including day-ahead scheduling, multi-day ahead planning, real-time dispatch and intra-day rolling dispatch. These procedures are deeply dependent on precise load projections, particularly in some coal-dominated areas where the unit commitment must be determined on a lengthier period base. The unexpected COVID-19 outbreak and the anti-epidemic regulations make the load demand more ambiguous and thus bring about more difficulties in load prediction. The impact of COVID-19 on the society and economy is exceptional in history, which makes the learning-based predicting tools non-flexible. The effect of regulations (both anti-epidemic controls and reopening obligations) must be completely assessed and highly deemed in the load forecasting to follow the changing aspects of the disease. The growing proportion of intermittent renewable sources also intensifies the ambiguity. Hence, a more flexible margin is mandatory in the generation schedule to prevent unforeseen changes in load demand and variation of PV and wind powers.

2.3. Voltage and frequency regulation challenges

The change in electric energy demand profiles and the low consumption results in adverse effects on frequency stability. The increase of the share of the RES and the deviations in frequency are prominent during the pandemic in some regions like Israel [63]. In addition, the problem of voltage regulation increases in the power system of some regions. Traditionally, the voltage decreases along with feeders without any distributed generators in distribution systems. With high penetration of the
DERs during COVID-19, the reversal power flow injected by the DERs may produce an upsurge and greater instabilities of voltage across the feeder [64]. The generation power from DERs like PVs and wind turbine persists at a similar amount although the electricity demand drops during the pandemic. The oversupply of net generation increases the voltage rise concerns in some distribution systems. This problem is mainly leading in some local regions with commercial buildings and large numbers of factories that are partially or fully locked during the COVID-19 outbreak [65]. For example, the voltage increasing produced by demand reduction and protracted load at a low level was noticed in South America by utilities. Analogous problem is also extensively concerned by power system operators in North America, India, and China [66]. Power system operators commenced the protective actions to protect the overvoltage of the grid in countries where a substantial load decline was witnessed. The voltage decline has been handled with regional load dispatch centres (RLDC) in India with utilizing (i) closure of capacitor banks and reactors at the distribution level, (ii) static VAR compensators and Static Synchronous Compensator (STATCOM) in voltage control method, and (iii) STATCOM for riveting excess reactive power [1]. The abnormal voltage level was decreased with these measures.
Table 1
COVID-19 impacts on power systems for different countries.

| Location       | First lockdown duration | Lockdown level | Electricity generation (GWh) | Impacts on power system demand |
|----------------|-------------------------|----------------|------------------------------|--------------------------------|
| Australia      | 23-03-2020              | State level    | 261,400                      | • In Victoria, the reduction of 1% and 7% of electrical demand in industrial and commercial sector is observed [51]. |
|                | 15-05-2020              |                |                              | • About 40% increase in residential demand was observed. |
|                |                         |                |                              | • In Victoria, the reduction of 1% and 7% of electrical demand in industrial and commercial sector is observed [51]. |
| Belgium        | 18-03-2020              | National level | 74,600                       | • Substantial load reduction of more than 70% loads in commercial and industrial sector was observed [52]. |
|                | 04-05-2020              |                |                              | • Financial support for payment of energy bills was provided. |
| China          | 23-01-2020              | State level    | 7,111,800                    | • The total electrical demand was 8%–9% less in January and February 2020 as compared to 2019 [53]. |
| France         | 17-03-2020              | National level | 574,200                      | • Substantial load reduction of more than 70% loads in commercial and industrial sector was observed [52]. |
| Germany        | 20-03-2020              | State level    | 648,700                      | • Overall electrical demand is reduced. |
| Italy          | 09-03-2020              | National level | 290,600                      | • Electrical demand is reduced by 22%. |
| India          | 25-03-2020              | National level | 1,561,100                    | • Share of renewable energy is increased to 40% [55]. |
| Singapore      | 07-04-2020              | National level | 52,900                       | • Electrical demand is reduced by 22%. |
| (New York City)| 29-03-2020              | State level    | 4,460,800                    | • Implementation is difficult. |
| Spain          | 14-03-2020              | National level | 25-04-2020                   | • Reliability issues and computationally expensive. |
|                | 20-03-2020              | National level | 275,000                      | • Reduction of about 4% sales of electricity to industrial sector [58]. |
| UK             | 23-03-2020              | National level | 333,900                      | • Residential demand is decreased by 20%. |
| USA (New York City) | 29-03-2020          | State level    | 4,460,800                    | • Implementation is difficult. |

Table 2
Different approaches are applied to handle voltage stability issues in the power system.

| Control strategy | Approach | Impacts on voltage stability issue of power system |
|------------------|----------|---------------------------------------------------|
| Conventional     | • Mode decoupling [68]. | • The proposed controlling strategy is efficient for fixed parameters or parameters within range. |
|                  | • Vector control [69]. | |
|                  | • Control loops [70]. | |
|                  | • Dual-STATCOM [71]. | |
| Nonlinear        | • Inverse system theory [72]. | • Implementation is difficult. |
| Soft computing   | • Metaheuristic [73]. | • Reliability issues and computationally expensive. |
|                  | • Fuzzy [74]. | |
|                  | • Fuzzy with particle swarm optimization (PSO) [75]. | |
| Adaptive         | • Adaptive law [75]. | • Nonlinear system dynamics are neglected. |
|                  | • Self-tuning fuzzy [74]. | |
| Robust           | • Optimal linear–quadratic regulator (LQR) [76]. | • Reduction of model order makes its implementation difficult. |
|                  | • Pole placement [77]. | |
| Hybrid           | • Centralized [78]. | • Less reliable with communication requirements. |
|                  | • Distributed [79]. | • Nonlinear dynamics and communication delay is ignored. |
|                  | • Decentralized [80]. | • Lack of coordination. |
|                  | • STATCOM and PV inverter control [81]. | |
|                  | • Distributed and centralized [82]. | • Complex computations. |
|                  | • Radial basis function neural network (RBFNN) [83]. | • Communication delay is ignored. |
|                  | • Centralized [78]. | • Complex with greater computational requirements. |

3. Identification of critical factors affecting the development of renewable energy sectors and markets in general and during the pandemic

In times of crisis, such as the COVID-19 pandemic and the associated economic recession, a well-functioning energy system provides a vital role [84]. The COVID-19 crisis has a significant effect on renewable energy facilities, supply chains and companies along with the slowing transition to cleaner energy [85]. However, the renewable energy sector has been less affected than the rest of the energy sector in the COVID-19 outbreak. The COVID-19 crisis has affected project developers, investors, and the renewable energy industries, considerably [86]. The COVID-19 crisis has affected various sectors such as power and energy, electronics, automobile, transportation, and education [87]. The COVID-19 pandemic also results in severe damages to the country’s economies in the short and long terms [88]. When the...
COVID-19 pandemic exponential spread in the world, a considerable drop in energy consumption has been observed, forecasting a scenario of sizable low-cost power generation, from the RES [89]. Besides, the energy consumption in buildings is decreased by shorter working hours [76]. Overall, in some countries, generation from nuclear, fossil coal and gas sources has reduced in favour of the RES and fossil gas [90].

Various factors can play a critical role in contributing to or affecting the development of the RES [91]. Technological development, pioneering activities of companies, society awareness and preferences, energy related policy, market demands are commonly mentioned drivers for the RETs development [92]. Many countries have tightened their budgets and delayed the implementation of renewable energy projects due to the effects of COVID-19 [93]. Compared with 2019, renewable electricity capacity in the first quarter (Q1) capacity of 2020 was lower for all technologies with solar PV and winds each contracting 25%, except hydro energy. Hydro energy capacity has increased inversely in the first half of 2020 (see Fig. 4) [94]. This section summarizes several factors affecting RES development in terms of the financing community and investors, electricity markets and prices, employment, heat, and transport in Fig. 3a. In addition, pushing and pulling forces for REP development is described in Fig. 3b.

3.1. Financing community and investors during and post COVID-19 crisis

The COVID-19 pandemic has a destructive impact on global economic growth mainly due to two factors. Firstly, the COVID-19 outbreak has delayed ongoing investment projects such as renewable projects, large energy infrastructure and energy efficiency projects due to loss of revenues, clients not being able to repay loans, supply chain disruptions. Secondly, governments have regulated human movement and restricted transport to prevent the growth of the epidemic and consequently reduced economic activity [95]. The COVID-19 crisis has been a significant impact on investment across the energy sector. In particular, the governments have played a significant role in shaping energy sectors’ rescue from the COVID-19 outbreak [94]. Pre-crisis planned projects and policies have at least as much influence as the COVID-19 pandemic on the future of the RETs. Robust financial performance is important for project developers and renewable producers to be offered a lower cost of capital to finance capital-intensive expansions. The stock market is one of the performance metrics that can show the rates of return and financial health, which requires a transparent method that evaluates the financial performance of companies. Renewable auction results are very high despite some delays during COVID-19. Fig. 5a and 5b depict...
the results of renewable electricity auction for renewable technologies and countries, respectively. In Europe, countries such as Italy, Germany, Portugal and France each fulfilled solar PV and wind tenders from January to June, but the capacities delivered in the region were remarkably lower than the previous year. In addition, Greece, Ireland, and the Netherlands performed tenders with delays as a result of the COVID-19 crisis. Thirteen (13) countries including China and India have granted about 50 GW of new renewable capacity to provide operational during 2021–24 in the first half of 2020 [94].

3.2. Electricity markets and prices

The economic slowdown, movement restrictions and lockdowns as a result of the COVID-19 outbreak have reduced electricity demand around the world remarkably [96]. Electric consumption has dropped by 23% in India, 18% in Spain, 12% in Germany and 5% in the United States in April 2020 relative to April 2019 [94]. As given in Fig. 6, the overall price level of most electricity markets has decreased considerably as a result of the reducing electricity demand and the slumping prices of natural gas and oil [97]. The COVID-19 crisis has created immediate and observable impacts on power markets [98]. The performance of different power markets in several countries in terms of the variable renewable energy (VRE), wholesale electricity prices and demand has been analysed globally for the months in Fig. 7a, b and c, respectively. As can be seen in CAISO and ERCOT markets in the United States, wholesale electricity prices have reduced dramatically.

3.3. Employment

The governments are enacting stimulus packages to deal with the increasingly dire circumstances during the COVID-19 crisis since company revenues are shrinking and millions of people have lost their job [99]. In many sectors of the economy, the COVID-19 outbreak has created a major impact on employment. Renewables jobs have been less affected than fossil fuel jobs within the energy sector. The importance of strong policy frameworks for the RES has been further reinforced by the COVID-19 outbreak to achieve economic, social and environmental goals. However, unemployment rates were high and rising even before the COVID-19 pandemic [100]. Solar PV energy, wind energy, bioenergy, liquid biofuels, wind, solar heating and cooling and hydropower have been the biggest employers [101]. The solar energy industry has been the largest employer among RETs. As shown in Fig. 8, more than 11 million people have been employed in the renewable energy sector globally directly and indirectly, while 3.3 million people have been employed in the energy efficiency industry across the United States and Europe alone [101].

3.4. Heat and transport

Heat, which accounts for half of global final energy consumption, is the largest final energy use, significantly more than electricity (20%) and transport (30%) [94]. Global heat consumption in homes and for industrial processes is estimated to decrease more than 3%, commonly because of the curtailment of economic activity. Renewable heat consumption reduces as well, but by only less than 1%, indicating a certain degree of resistance to the crisis. Owing to a combination of oil prices and lower transport activity, the use of biofuels declines most of all RES because of the COVID-19 crisis. The EVs can be more widely used with decreasing health risks compared to shared transport or traditional taxis by reducing human contact [99]. Fig. 9 shows the change of total energy demand and renewables output in electricity, heat and transport sectors [94]. Diesel consumption 7% drops 9% and global gasoline demand while jet fuel demand falls about 40%. Biofuel production is expected to decrease a record of 11.5% in 2020 compared with 2019.

3.5. Geographic limitations

The location of geography acts a remarkably important role in specifying the availability of the RETs. Some RES is kept in view
to be abundant in some places while another RES has seriously restrained in other places [102]. For instance, hydro energy is an important part of the REP in areas close to rivers while hydropower plants have not existed in areas with no rivers close. Similar geographic restrictions can be found for other RES such as solar energy, geothermal energy, wind energy, ocean energy and bioenergy. In literature, many studies have been addressed to specify the availability of the RES [103]. On the other hand, wind energy potential depends on both different geographic regions and the height of wind turbines from the ground. Restrictions on geographical eligibility also can result in more volatile and less liquid renewable energy certificate markets [104].

3.6. Dispatchability

Dispatchable generation is one of the types of electricity production that can be dispatched depending on the electricity demand. Furthermore, dispatchable generation can be beneficial to cover intermittent RES when the demand is high. Wind energy, wave energy, solar energy and tidal energy are some examples of highly intermittent RES. Since electrical production from wind turbines and the solar cell can be affected by external conditions like wind speed and atmospheric conditions, hours of the day, geographical location, they are highly non-dispatchable. On the other hand, wave energy and tidal energy are also intermittent power generation as their power generation is highly dependent on waves and tides [103]. Energy sources cannot be associated with a long-term storage system, having intermittent generation characteristics are non-dispatchable and should be set to work at the point of maximum power and normally connected to the network with inverters. Non-dispatchable energy sources influence the dynamic stability of the systems [105].

3.7. Scalability of renewable energy

The size of the power plant has an extreme influence on the performance of renewable energy systems. Even though similar prime mover technologies can be utilized for power plants with different capacities, efficiencies of the overall plant, capital and operating costs are not enforcedly the same [103]. Moreover, projected costs, social indicators, environmental indicators, reliability indicators and expected energy performance have also influenced the size of renewable energy generation. The feasibility of the
technology at large-scale setups can be determined by the scalability of the renewable energy systems [106]. In particular, for the long-distance transmission of large-scale renewable energy, voltage source based power electronic converter—high voltage direct current provides effectual solutions [107]. Moreover, the large-scale integration of RESs like wind energy and solar energy into the grid leads to great challenges for the electricity grid [108].

3.8. Capacity factors and energy storage

The capacity factor is a remarkably important measurement for the RETs, which is defined as the ratio of actual electricity generation to the maximum potential output of a power plant. The capacity factor of a power plant is frequently less than 100% because of several factors. The RES is not available all the time.
to be utilized for power generation. The low wind speed and not blow wind affect electricity production from wind turbines. Similarly, solar energy production is very intermittent because of the different weather climates and conditions, consisting of heavy rain, hail, wind, heat and cold. Another factor affecting the capacity factor of renewable energy facilities is the market demand [103]. The electrical energy generated more than demand has to be stored otherwise it cannot be utilized later and the cost of generation for that portion will go waste. Electricity produced from the RES such as wind and solar highly requires storing excess energy since solar energy at night and wind energy will not exist at certain times [109]. Power generation from highly variable RETs can be difficult. In particular, energy storage devices are required to store the excess energy produced by the RES for the high variability of renewable energy [110]. However, the expansion of variable wind and solar energy is restricted by using excessive electricity storage requirements [111].

4. Results and analysis of the electric energy demand in the light of the COVID-19

The countries have taken numerous actions, including social distancing, travel restrictions, and the industrial energy sector’s closure to control the spread of the COVID-19 [112]. The pandemic has direct and indirect impacts on the social, technological, economic, environmental and energy-related changes [113]. These limitations cause significant variations in electricity demand. Electricity demands in homes increased while commercial and industrial demands decreased due to restrictions on the commercial and industrial businesses and “stay at home” plans [114]. Rising energy costs, energy production and higher energy consumption have a broader effect on societies around the world [115]. Fig. 10 presents the daily electricity consumption from January to May for 2018, 2019, and 2020, respectively, in three countries such as USA, Italy and Japan. In comparison with profiles of 2018 and 2019, the electrical load in the USA and Italy indicates a significant reduction. The lockdown restrictions in Italy were published on 8th March 2020 for the north part of the country and were spread out on 10th March 2020 to the whole country.

The limitation policies distinctly affected the variation of electricity consumption in the country. As shown in Fig. 10b, during the second week of March when the full quarantine was implemented, peak daily electricity consumption fell by about 20% in Italy (The data used in Fig. 10 considered based on [97]). The demand reduction was observed in the USA after 1st April 2020. It is evident from Fig. 10b; the daily electrical peak demand was approximately dropped by 20% when the full lockdown was announced in the second week of March. Afterwards, the demand has approached the 2019 level and gradually increased. However, the recovery observed in the USA was not considered to last year level. However, a similar trend was not noticed in Japan, as shown in Fig. 10c as a result of a partial lockdown policy and different actions taken by the government of Japan [116]. The variability in electrical demand is computed by the coefficient of variation as investigated in [117]. As shown in Fig. 11, the annual variability of the electric energy demand of 2018 and 2019 with 2020 is examined and investigated. There is a reduction in electric energy demand for months of the year 2020 for the USA, Italy and Japan as depicted in Fig. 11a, 11b and 11c.

4.1. Variations in load composition and demand profiles

The composition of the electrical load has altered in different countries during the lockdown. The industrial sector utilizes less electricity with the suspension of production. In the USA, the electrical energy required in industrial and commercial sectors has dropped by 20% during 2020. Also, in the manufacturing industry of China, electrical demand reduction has been observed by 13%. In spite of this, the increase in residential load has been observed among most nations with safety guidelines in some European countries. Residential energy consumption has increased by approximately 40% [118]. The load profiles have also been re-shaped as well as the change of load composition in various regions. The variations in load profile during the first week of April in 2020 and 2019 for NYC can be visualized from Fig. 12. The region was badly affected by the epidemic and imposed lockdown from 22nd March 2020. As can be seen in Fig. 12a, the decrease in peak load has about 13% on weekends and 21% on weekdays. The variations in the shape of the load profile and the load decline were also considered. The daily peak demand was usually observed in the morning hours during weekdays in 2019. It can be seen from Fig. 12a that the peak demand was suppressed and shifted to late hours after 2020 lockdown implementations. However, the peak demand became predominant during evening peaks. The load profile is modified with the closure of commercial and residential users. The analogous change was also detected in other territories. The comparison of load profiles was observed for Spain and Italy during pandemic lockdown restrictions and 2019 year [119]. In Italy, the peak load was decreased to about 10% on weekends and 20% on weekdays after full lockdown. After the first week of industry closure, a 14% drop in peak load was examined. Also, the energy demand on weekdays is similar to weekends demand with a slower morning peak ramping rate. With the increased share of solar generation and demand reduction, an aggravation of the “duck curve” was detected in California, USA [120]. To observe the correlation between electrical demand reduction and pandemic for NYISO, a backcast method is proposed in [121]. Annual variability of electric energy demand between April month of the year 2019 and 2020 are also investigated and examined in Fig. 12b. It can be observed in Fig. 12b that energy demand has reduced in 2020 as a result of the pandemic.
22% of the global electricity demand. The industry sectors supply around 42% of the global electricity demand. Both these sectors are accountable for approximately equal shares of the electric demand in advanced economies [122]. In particular, economic structure achieves a considerable role in specifying the impact of the COVID-19 pandemic on the economy and electricity demand. While industry sectors possess around half of the energy demand in emerging and developing economies, the public services and commercial sectors compose around 14%. The average growth of electricity demand fell by over 2% in 2020. Global electricity demand decrease has been avoided by getting better in China and to a lesser extent in India. As shown in Fig. 13, the greatest global decline had been observed in Europe by more than 4% in 2020. The Asia Pacific, with reductions in India (2%), Korea (3%) and Japan (around 4%), is responsible for 48% of global electrical demand. On the other hand, electrical demand in North America observed by 3% decline and the reduction in the Middle East is equable (see Fig. 13).

In the 2009 global financial crisis, the most recent global economic crisis before the COVID-19 pandemic–electricity demand fell by 0.6% (net 103 TWh), and global real gross domestic product (GDP) reduced by 0.1% [122]. Although electricity demand in emerging and developing economies continued to expand by 3.6%, it dropped by 3.8% in developed economies, as shown in Fig. 14a. On the other hand, renewables and nuclear maintains to diminish the rest of fossil fuel generation in advanced economies. As depicted in Fig. 14a and b, global real GDP growth has been dropped by 3% in 2020, while it will be estimated by 6% in 2021.

Fig. 10. Electrical demand profiles comparison for (a) the USA, (b) Italy and (c) Japan.
4.2. The impact of the COVID-19 on the energy consumption during heating and cooling degree days

The COVID-19 does not influence temperatures, but affecting the number and type of buildings that require to be get for cooling degree days (CDDs). People who generally close their air conditioners while at work have turned on the air conditioners to continue working from home due to the COVID-19. Therefore, COVID-19 does not affect CDDs, but rather energy consumption and where to place the load. Besides, the COVID-19 has an effect on the load placing for heating degree days (HDDs) during warmer winter season. More people may become back to their place of business as the pandemic progresses and restrictions are relaxed, leading to higher energy demands to warm buildings [123]. Weather-adjusted time series data of electricity demand pre- and post-COVID-19 lockdowns are utilized to identify the magnitude of changes in electricity demand and residential energy use patterns.

The HDDs and CDDs calculations play a vital role in finding a specific location of heating and cooling demand. The selection of base temperature \( T_B \) in these indices computation is the main factor. Its choice depends upon the building and climate in that region. \( T_B \) can be specified by using the performance line or energy signature method. There is a plot between mean temperature and electric energy consumption in the energy signature method. The intercept of weather independent and dependent electrical demand represents \( T_B \). However, the performance lines are the best fit straight lines between CDDs or HDDs and electrical energy consumption. \( T_B \) is calculated by best fit 2nd order polynomial through scatter plot between CDDs or HDDs indices versus the electrical demand with \( T_B \) variations until the polynomial approaches suitable linearity. Conventionally, \( T_B \) is 18.3 °C in the United States, 15 °C in Germany, and 15.5 °C in UK.
Fig. 12. Electrical demand comparison for NYC during weekdays in April 2019 and 2020; (a) electrical demand of the year 2019 and 2020 separately and (b) annual variability of electric energy demand between April month of the year 2019 and 2020.

Fig. 13. Average growth of electricity demand for historical and 2020 around the world.
calculate the CDDs and HDDs [124]. These indices are also usually estimated at arbitrary \( T_B \) or using a \( T_B \) of 18 °C as a comfort temperature. In this study, \( T_B = 18 \) °C has been selected based on Ref. [125] for NYC. A baseline regression illustrates energy utilization over a selected baseline period and is usually used to assess later energy utilization against baseline stages (e.g., to pursue current implementation or prove energy savings from changes in cooling or heating appliances made after the reference period).

Energy demand can be estimated by CDDs and HDDs method to observe electricity consumption as explored in [126]. Electrical demand requirements vary depending upon the temperature variations above or below the base temperature. Several methods have been explored to observe degree days in literature, whereas the degree hour or hourly method is the most effective method for these indices’ computation [127]. Daily values of the CDDs can be given by (1) and (2) as:

\[
CDD_d = \frac{1}{n_h} \sum_{i=1}^{n_h} C_i
\]

\[
C_i(h) = \begin{cases} 
O_T - B_T, & \text{if } B_T < O_T \\
0, & \text{if } B_T \geq O_T 
\end{cases}
\]

where \( B_T \) and \( O_T \) are the base temperature and daily hourly temperature, respectively. \( i \) is the specific hour and \( n_h \) is total number of hours. Similarly, the daily HDDs values are calculated by using (3) and (4) as:

\[
HDD_d = \frac{1}{n_h} \sum_{i=1}^{n_h} H_i
\]

\[
H_i = \begin{cases} 
B_T - O_T, & \text{if } B_T > O_T \\
0, & \text{if } B_T \leq O_T 
\end{cases}
\]

The hourly differences between \( O_T \) and \( B_T \) can be attained during each day for all months to calculate the monthly and annual CDDs and HDDs. The monthly degree days \( DD_m \) can be calculated by (5) as:

\[
DD_m = \sum_{j=1}^{D} DD_{d,j}
\]

where \( j \) indicates the number of days. Similarly, the annual degree days \( DD_y \) can be estimated by (6) as:

\[
DD_y = \sum_{k=1}^{12} DD_{m,k}
\]

where \( k \) indicates the number of months. However, degree days can be calculated from reduced datasets with respect to daily mean, maximum, minimum temperatures, or standard deviation of temperature. The hourly method of the degree-day’s computation is more precise as compared to conventional methodologies. However, the selection of base temperature \( B_T \) depends upon buildings construction designs and climatic variables such as humidity, wind etc., for different counties.

The relationships between energy consumption profile and outdoor air temperature are described in Fig. 15. Fig. 15a and 15b depict linear and nonlinear asymmetric models, respectively [128]. Fig. 15c shows winter (cold climate) and summer-peaking (warm climate) utilities. Cooling (\( S_{CL} \)) and heating (\( S_{HL} \))
Fig. 15. Relationships between energy consumption profile and outdoor air temperature; (a) linear symmetric model, (b) non-linear symmetric model and (c) utility loads. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

load sensitivities, threshold ($T_{DD}$), and base loads ($B_L$) temperatures are also indicated in Fig. 15. Shaded areas (red and green) point out temperature ranges over where the load is least sensitive to alterations in outdoor temperatures [129].

The base temperature of ($65^\circ F = 18.3^\circ C$) is a neutral base temperature selected for CDDs and HDDs calculation of NYC because it is appropriate for the comfort of users and is usually not too cold and hot. Also, this base temperature is selected based on the international standard recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers [130]. The impact of variations in base temperature from 15 $^\circ C$ to 20 $^\circ C$ on degree days has been analysed to observe different outcomes. The same base temperature can be used for CDDs and HDDs calculation [131]. The hourly base temperature with an increment of 1 $^\circ C$ has been considered from 15 $^\circ C$–20 $^\circ C$ to observe the variation in degree days average results for five consecutive years from 2016 to 2020 in Table 3. The greater value of indices has been observed in July and January, indicating that the greater energy demand is required for both summer and winter in these two months. The estimation of the energy demand based on CDDs and HDDs is indicated in Table 4. Base temperature ($T_B = 18^\circ C$) for location (NYC) has been used for calculation of these indices for years of 2017, 2018, 2019, and 2020. With increasing in base temperature values, the increment in the HDDs values and decreasing in the CDDs values have been observed as depicted in Table 4. Furthermore, during June, July, and August, it has been noticed that CDDs are higher for each base temperature value, which results in increased energy consumption during the summer season. Besides, the greater utilization of heating appliances during the winter months is the primary cause of the increase in the electric energy demand.

4.3. Impact of climate change on energy demand

The energy sector is also central to attempts to struggle the climate variations [132]. Supporting sustainable development has become an essential part of policy making, energy planning and analysis along with struggling climate variations during the pandemic. Because of the COVID-19 crisis, as shown in Fig. 16, global CO2 emissions are largely looked ahead to drop by 8% in 2020 or nearly 2.6 gigatonnes (Gt) to levels of 10 years previous ago. This reduction results in a record level since 2010 and is six times larger than the record drop of 0.4 Gt in the 2009 financial crisis. Previous reductions in CO2 emissions have been half of the reductions in 2020 since the end of World War II [133].

All of the drops in energy demand in 2020 have not been owing to the response to the COVID-19 pandemic. Energy demand has been declined with the extension of milder than average weather conditions along nearly all of the Northern Hemisphere winter. As can be seen in Fig. 17, full lockdown measures have declined daily electricity demand by a minimum of 15% in the northeastern region of the United States, Spain, India, France, Italy and UK after convenient weather conditions. Electricity demand dropped in Europe, Korea, the United States, and Japan in 2020 compared to 2019, not only due to the COVID-19 pandemic but also since weather conditions in January and February were more moderate than in 2019. In China, compared to February 2019, electricity demand fell by $−13%$ in January and more severely in February. Part of the difference is that February is notably colder in 2019 than in 2020. After the weather corrected, the electricity demands stayed in June (10%) and July (5%) below the same months of 2019 in most countries except India. While the weather corrected, the drop in electricity demand was still $−11%$ in February 2020 compared to February 2019. Electricity demand provided the first signs of recovery after restrictions measures were eased. From August 2020 on, demand was 6% higher after the convenient weather conditions. Electricity demand in India increased by more than 3.4% in September 2020 compared to September 2019 along with high demand in the industrial and commercial sectors and good weather conditions. While full lockdown measures have decreased electricity demand...
Table 3
Average values of the CDDs and HDDs from 2016 to 2020 with varying base temperature in NYC.

| Months/°T | CDDs | HDDs |
|-----------|------|------|
|           | 15 °C | 16 °C | 17 °C | 18 °C | 19 °C | 20 °C | 15 °C | 16 °C | 17 °C | 18 °C | 19 °C | 20 °C |
| January   | 19 | 13 | 11 | 8 | 7 | 5 | 232 | 259 | 286 | 312 | 315 | 327 |
| February  | 44 | 33 | 28 | 22 | 19 | 15 | 151 | 170 | 192 | 211 | 214 | 221 |
| March     | 94 | 75 | 62 | 49 | 44 | 42 | 70 | 85 | 102 | 112 | 115 | 119 |
| April     | 147 | 122 | 103 | 84 | 78 | 71 | 24 | 28 | 35 | 56 | 58 | 62 |
| May       | 265 | 233 | 206 | 179 | 167 | 165 | 2 | 3 | 5 | 9 | 11 | 14 |
| June      | 393 | 361 | 333 | 303 | 300 | 298 | 0 | 0 | 0 | 0 | 0 | 0 |
| July      | 477 | 445 | 415 | 385 | 376 | 370 | 0 | 0 | 0 | 0 | 0 | 0 |
| August    | 458 | 425 | 396 | 365 | 364 | 359 | 0 | 0 | 0 | 0 | 0 | 0 |
| September | 370 | 338 | 310 | 281 | 278 | 271 | 0 | 0 | 0 | 1 | 3 | 5 |
| October   | 198 | 172 | 152 | 131 | 127 | 125 | 26 | 33 | 42 | 51 | 55 | 58 |
| November  | 71 | 55 | 45 | 35 | 32 | 31 | 90 | 105 | 126 | 142 | 146 | 149 |
| December  | 28 | 20 | 17 | 13 | 11 | 10 | 181 | 204 | 233 | 256 | 259 | 263 |
| Total     | 2564 | 2292 | 2078 | 1855 | 1803 | 1762 | 772 | 887 | 1015 | 1156 | 1176 | 1218 |

Fig. 16. Annual change of CO2 emissions related and global energy demand in 1900–2020.

by 20% or more, partial lockdowns have smaller effects. Implemented strict measures created the largest impacts in economies where services constitute a larger part of the economy. Electricity demand is declined by over 25% in Italy during both full and lockdown measures. On the other hand, during the first prevention phases in Europe and the United States and continuing measures in Japan, partial lockdown measures constituted fewer impacts on electricity demand about 10% [133].

4.4. Declines in energy demand with increasing energy efficiency/energy intensity

Energy efficiency performs a crucial role in promoting clean energy transitions and providing sustainability goals and global climate. Energy intensity takes the measurements of the energy efficiency of the economy and indicates how much energy is required to manufacture a unit of the GDP, which declines with the decreasing of energy demand [134]. There are three main factors to promote the improvement of energy efficiency. First, the improvements of the technical energy efficiency are of great importance to balance nearly half of the possible increase in worldwide energy demand as a result of the economic growth. Second, global economic growth reduces the size of the “activity effect”, which is an increase in energy demand. Third, more temperate weather decreases the need for coal, gas and electricity for heating and cooling, reducing energy demand. The combination of more efficient technologies and processes diminishes energy demand and increases energy efficiency, resulting in less energy usage. As depicted in Fig. 18, energy usage has been down with decreasing 15%–19% overall. Although the COVID-19 crisis...
has largely decreased energy demand in commercial buildings, energy demand widely changes with regions, business sizes and customer segments. Commercial buildings such as restaurants, supermarkets and hospitals that require more energy-intensive have suffered from a less severe reduction in energy demand. Smaller businesses are crucial nature and services are greatly impacted as compared to larger businesses [135]. While the largest businesses with over 10GWh yearly have only drop 13%, small businesses have been the most affected with 30% energy declining. Energy demands for services, similar dry cleaners have experienced a 45%–54% decrease and a decrease of 33%–46% has been observed for education. Healthcare and banking are down 9%–16% decrease (see Fig. 18).

4.5. Variations in electricity price

The price level of electricity has experienced a remarkable decrease owing to the electrical demand reduction and the declining prices of oil and gas since March 2020. The electricity markets in some European countries suffered the most serious price slump, with monthly average prices dropping to the least in the previous six years. The relative change of electricity prices in major electricity markets across Europe during April 2020 concerning April 2019 and March 2020 can be portrayed from Fig. 19. It has been observed that, compared with March 2020, the drops are 42.5% in the France EPEX SPOT market and the drops for the UK N2EX market are about 21.8%. However, the drops appear much severest when compared with April 2019. The declines exceed 51% for most of the markets, among which the most prominent is 86.5% for the Nord Pool market [136]. The electricity prices in the USA have also dropped intensely with the rapid spread of COVID-19. The trends of average daily locational marginal prices (LMPs) across major independent system operators can be visualized from Fig. 20.

Daily LMPs have dropped since February as a result of partly weather conditions and partly COVID-19 across several independent system operators (ISOs). Seasonal and COVID-19 implications of decreased production in the spring fall mainly on coal power plants and natural gas. Pennsylvania–New Jersey Maryland (PJM) interconnection noted an average of 8% reduction in load relative to the past 5 year average and days are like snow days with flatter curves and later peaks [137]. MISO has stated a 3.8% load drop since March 22. The California ISO (CAISO) serves residential, industrial and commercial customers in 80% of California and a small portion of Nevada [138]. The profile of the CAISO net electricity demand traces a duck curve as a result of the high penetration of renewable resources as depicted in Fig. 20. In addition, CAISO stated that the decrease was the least on weekend days, with a reduction of approximately 1.3%. To determine the effect of the stay-at-home order on energy sales and peak demand, the CAISO conducted its weather analysis specifically for March 23–March 29, 2020. The CAISO reports nearly load drop of 4%–5%; lower peaks for the morning, midday and evening peak down are 6%–7%, 4%–5% and 23%, respectively. When the crisis appeared in March, the ISOs commenced reporting load drops, and midcontinent ISO (MISO) indicated a %9–13 drop in daily weekday demand compared to temperature-matching days in March 2019 [139]. CAISO utilizes a backcast model to isolate the impact of the stay-at-home order, eliminating the largest familiar sources of weather forecast errors [140].

A significant decline of about 10%–12% was observed during late March [141]. Also, a notable reduction of about 20% was observed in the market-clearing price during the first few days of lockdown in India [1]. In addition to price decrement, negative price incidents also happen during the pandemic. A
reduced electrical demand threatened power system resilience and power system stability was difficult to manage by demand response programmes. In addition to this, the prices of electricity become volatile in the Northern Hemisphere during spring due to the abundance of wind and solar. The negative hourly prices were frequently observed, especially during the noon of the day, in many European countries. For instance, the lowest price was recorded on 13th April 2020 in Belgium EPEX SPOT market of about –€114.31/MWh. Besides this, Germany has undergone 128 h of negative price during the first quarter [97].

4.6. Financial circumstances faced by customers

Coal-fired power sources have suffered the most on the generation side during the pandemic. The international energy agency (IEA) estimated that the output of coal fired power plants have dropped significantly after the beginning of lockdown policies. The total usage of coal-fired consumption in the 1st quarter of 2020 dropped by 8% compared to the 1st quarter of 2019. About 3.5 GW of coal-fired capacity has been wasted in the UK with a loss of profit [142]. The financial status of most customers has been affected during lockdown restrictions on the demand side. However, governments all over the world have struggled to assure electric energy for customers. In [143], governments provide some actions to ease the electricity bill burden of customers. Nearly all utilities present bill payment delays either willingly or forcibly. However, utilities are experiencing a relatively tough time. Besides, the revenues of utilities get reduced because of both decreased demand and lowered market prices. On the other hand, regular operational maintenance costs of the system rise under such a specific situation. Stock prices of USA utility have altered about the same as the overall market, declining by 10.9% from 1st March to 10th April. Similarly, distribution companies in India have experienced a net revenue loss of 200 to 300 billion rupees approximately [144].

The COVID-19 has a significant influence on electricity demand in most European countries such as Spain, Italy, and France with the rigorous spread of the virus. As shown in Fig. 21a, the major European countries have considered the reductions in the electric demand such as Spain (6.4%), Italy (14.8%), France (11%), Portugal (6.9%), Belgium (6.1%), Netherlands (4.9%), Germany (4.8%) and UK (5.9%). As depicted in Fig. 21b, some other major countries have declined in the electric demand such as the USA (25%), Singapore (7.8%), Australia (5.6%), India (7.9%) and China (6.8%).

4.7. Impact of the COVID-19 crisis on the electrification of the transport sector

The EVs have a high potential to decrease greenhouse gas emissions and to attain other benefits such as promoting energy security and reduction in local air pollution [145]. The penetration of the EV appears to be a future reality in the global transportation sector, which comprises of substantial increment in electricity demand [146]. Besides, the EVs quickly expanded in recent years to maintain alternative solutions for energy demand, domestic and industrial applications [147]. Recently, EVs utilizing advanced battery charging technologies are used as grid-combined energy storage systems to command energy with greater flexibility and ensure grid services [148]. Wind energy, fuel cell energy and solar power emerge as the main technologies to fulfil the increased electricity demand collaborated with EV penetration [149]. However, EV deployment includes a relatively
small part of the electricity demand [57]. Several Association of Southeast Asian Nations (ASEAN) countries like Brunei, Malaysia, Thailand, Brunei Singapore, and Darussalam already reached full electrification and the percentage of electrification is 99 for Vietnam. Also, various other regions like the Philippines, Lao People’s Democratic Republic (Lao PDR), and Indonesia are expected to achieve full electrification by 2025, as shown in Fig. 22. With the decreasing electrification rates in Myanmar and Cambodia, they design some policies and federal proposals to accomplish 100% electrification in Myanmar by 2030 and in Cambodia by 2020 [150].

Public transport in cities has been seriously affected by the COVID-19 outbreak. The number of passengers decreased, with usage falling by 50%-90% around the world as metro and bus services lessened. After the lockdown, services should be achieved to ensure as much capacity as possible while providing safety and security for those who rely on the metro, light rail and bus [151]. During quarantine, the use of shared micro mobility has declined drastically and operators have diminished or put aside services, but shared bicycle use has increased significantly in Chinese cities, especially with the lifting of quarantine measures. Lockdown measures affected manufacturing facilities and supply chains and consumer demand in the first half of 2020. As can be seen in Fig. 23, over the first half of 2029, worldwide sales of electric cars were approximately 15% higher than in the same period in 2020 [152].

The COVID-19 outbreak and the providing economic crisis have greatly affected the global market for all types of cars around the world [153]. New car registrations fall by about a third compared to the previous year in the first part of 2020. In the second period, it was partly balanced by strong activity, resulting in a 16% year-on-year reduction. In particular, the share of global electric car sales increased by 70% in 2020 to a record 4.6% with traditional and general new car registrations declining [153]. In 2019, with a noticeable slowdown, the number of light EVs around the world increased by 9% relative to 2018. Fig. 24 shows the electric car registrations based on the propulsion types such as battery EV (BEV), plug in hybrid EV (PHEV) and fuel cell EV (FCEV) around the world between 2010 and 2020 [154]. In China, the overall car market has been less affected by the epidemic than in other regions. In European countries, BEV registrations proceed to exceed PHEVs, accounting for 54% of registrations of the electric car in 2020. Although registrations of the electric car dropped less than the overall market, the car market in the USA decreased 23% in 2020. On the other hand, the worldwide FCEV stock raised 40% in 2020 with increase in the number of hydrogen refuelling stations by Japan and China [155].
5. Conclusions and recommendations

This study offers insights into the progress, impact analysis, challenges and new perceptions for electric power and energy sectors in the light of the COVID-19 pandemic. The impacts of COVID-19 on electric power and energy sectors are primarily reflected in three aspects: power system operation issues, critical factors affecting the REPD and electric energy demand. Power systems and the energy sector confront unexpected events owing to significant variations in electric energy demand and some vulnerability in the power systems has been revealed during the pandemic, but COVID-19 also provides an opportunity to maintain resilient power sector planning with sustainable and reliable energy. The analysis and results outlined above ensure an overview of how satisfying energy demand, enhancing renewable energy scenarios played out, adapting to rapidly changing situations resulting from the COVID-19 restrictions. The results show that the electric energy markets and renewable energy sectors have been influenced badly in nearly all the countries in the world during the unlikely COVID-19 pandemic. In addition, various implications for variations in electric demand and power system operation in different countries during COVID-19 have been discussed in detail in Table 1. Some critical observations and insights are also highlighted based on the outline of the challenges and influences of the pandemic on energy demand and power systems as follows:

- The changes in load profiles and load composition have resulted in challenges for the power system operation.
- Impact of the weather conditions, partial lockdown and full lockdown measures taken by the governments on the electricity demand are observed and analysed during the COVID-19 pandemic. While the daily electrical peak demand was approximately dropped by 20% with the full lockdown measures, transition to partial lockdown measures had lesser impacts. On the other hand, convenient weather conditions increase electricity demand but, the electricity demands remained in June (10%) and July (5%) below the same months of 2019 in most countries.
- Electric consumption dropped by India (23%), Spain (18%), Germany (12%) and the United States (5%) in April 2020 compared to April 2019.
- The CDDs and HDDs have been used as a filter to compare energy consumption during the winter and summer season for the different years. The CDDs are higher during the summer seasons, which cause high energy consumption. Also, the greater utilization of heating appliances increases the usage of electric energy during the winter season.
- Critical drivers and barriers forces including the COVID-19 for REPD have been determined and discussed with extensive literature research to enhance the deployment of renewable energy.
- Serious consequences of the pandemic on continuing investment projects and investment plans have been examined.
- Energy demand reduction has been observed in most countries as shown in Figs. 6–15 and 18.
- The electricity prices in the major energy markets of non-European and European countries have dropped extremely with the rapid spread of COVID-19.
- The impact of climate change on the electric energy demand has been observed and examined during the pandemic.
- Reduction in the energy demand has been analysed and explained with increasing energy efficiency.
- Direct impacts like power demand and indirect impacts such as new projects, consumer relations and investments during the COVID-19 pandemic have been investigated and discussed in detail.

While this pandemic continues, the seriousness and long-term impacts of the COVID-19 outbreak on the electric energy industry, a considerable area of future research, continue to be seen. Lessons learned from this epidemic will specify new policies and long-term consequences towards a more sustainable future and
will avoid coming new crisis. A flowchart of the recommendations for the operational and management of the electric energy sector post-COVID-19 is shown in Fig. 25 [1]. In this regard, the research and practical studies for future studies can be pointed out in the following captions:

- Enhancing deployment RETs.
- Providing interest in the nuclear industry.
- Providing microgrid to control future power system management.
- Support for the electrical energy markets and renewable energy sectors.
- Investing in driving forces of renewables’ development.
- Focus on the power grid planning regarding the case of severe future pandemics.
- Enhancing power system maintenance.
- Planning and issues related to smart cities development.
- Integrating the complete electric system with the smart grid technology to restore power disturbances quickly and better utilization of the RESs.

- Clustering bigger urban areas or industrial zones with microgrids to deal with future power system management and to produce own energy during a period of lockdown.
- Incorporating the digital transformation of the energy sector into policies to accelerate reconstituting the power and energy sector.
- After the COVID-19 pandemic, taking steps to re-boost the economy utilizing greener alternatives due to the production rate of oil.
- Pointing out primary issues related to the impact of the pandemic lockdown on the grid stability, load forecasting, frequency deviations, electricity generation and electricity price.
- The COVID-19 implications on power system operation, control, and planning can be considered, addressed and discussed. A flexible power system can take into account scenarios with long-term reductions in electricity consumption for generation and transmission planning.
- It is crucial to develop load forecasting tools for the power system operations that take into account socioeconomic factors such as pandemics, stock market and re-integration plans.
• New technologies such as RESs, EVs and storage devices can be more integrated into the power systems.

CRediT authorship contribution statement

Doğan Çelik: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing.

Mehmet Emin Meral: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing.

Muhammad Waseem: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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