

## Article

# Effects of the COVID-19 Pandemic on Energy Systems and Electric Power Grids—A Review of the Challenges Ahead

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**Abstract:** The COVID-19 pandemic represents not just a global health crisis, but may signal the beginning of a new era of economic activity, the potential consequences of which we currently do not fully understand. In this context, the mid-to-long-range impacts of the pandemic on the energy sector have been studied extensively in the last few months. Despite these efforts, the pandemic still raises many open questions concerning the long-term operation and planning of power systems. For instance, how will the pandemic affect the integration of renewable energy sources? Should current power system expansion plans change in light of the COVID-19 pandemic? What new tools should be provided to support system operators during global health crises? It is the purpose of this paper to better understand the many aspects of these open questions by reviewing the relevant recent literature and by analyzing measured data. We point out the main challenges that the pandemic introduced by presenting patterns of electricity generation and demand, frequency deviations, and load forecasting. Moreover, we suggest directions for future research that may assist in coping with the mentioned challenges. We hope that this paper will trigger fruitful discussions and encourage further research on these important emerging topics.

**Keywords:** COVID-19; coronavirus; SARS-CoV-2; pandemic; health crisis; power system stability; renewable energy; energy market; energy policy; load forecasting



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## 1. Introduction

On 30 January 2020, the World Health Organization declared the 2019 Coronavirus disease (COVID-19) to be a public health emergency of international concern [1]. The energy industry as a whole reacted very quickly and effectively to the pandemic. There was a clear understanding that delivering reliable electric power is an essential service, and that interruptions would have huge impacts that should be avoided at all costs [2,3].

The COVID-19 pandemic represents not just a global health crisis, but may signal the beginning of a new era of economic activity, the consequences of which we currently do not fully understand. In this light, the mid-to-long-range impacts of the pandemic on the energy sector have been studied extensively in the last few months. As any complex phenomenon, the COVID-19 pandemic may be studied using bottom-up synthesis, in which global trends are studied by observing local behavior, or using top-down analysis, in which trends are explored based on fundamental principles. Many examples for both of these approaches can be found in the recent literature. The bottom-up research approach has been implemented by studying the effects of the pandemic on power systems in several countries, such as the United States [4], China [5], Italy [6], Spain [7], Brazil [8], Canada [9], India [10], Sweden [11], Israel, Estonia, and Finland [12]. One clear trend emerging from these works is the effects of the pandemic on energy consumption patterns and peak demand,

mostly due to the preventative measures taken by governments [13]. As part of this trend, many countries reported a significant reduction in electricity consumption in both the commercial and industrial sectors [14], which introduced numerous challenges to electric utilities and system operators [2,3]. Some of the challenges are a direct result of the irregular consumption patterns, e.g., high voltage levels and inaccurate load forecasting, whereas some of them are the indirect result of an effectively higher share of renewable energy generation, e.g., high ramp rates and fluctuations in frequency. In addition to the bottom-up approach, several top-down research efforts include new forecasting methods [15], long-term business impacts [2], the general effects of fast economic transitions [11,16,17], possible uses of machine-learning technologies [18], and the challenges related to the changing energy mix [2,12,16,19]. All the works mentioned above, as well as other works related to the impacts of the COVID-19 on energy systems and markets, are summarized in Table 1. The table presents the main focus of each work, as well as the geographical region of the study and the challenges discussed. As can be seen, the recent literature studies a wide variety of topics, including system operation, system planning, energy policy, energy markets, and additional sub-topics. Moreover, the number of papers that review each topic is more or less the same, and so the challenges are evenly represented. The references in Table 1 are presented in Table 2 according to their geographical scope. The table shows that currently most of the works focus on North America, Europe, and Asia.

Despite these ongoing research efforts, the pandemic still raises many open questions concerning the long-range operation and planning of power systems. For instance, how will the pandemic affect the global transition to a low-carbon economy, and, in particular, the integration of renewable energy sources? What will be the consequences for frequency stability? Should current power system expansion plans change in light of the COVID-19 pandemic? What new tools should be provided to support system operators during global health crises? The purpose of this paper is to better understand the many aspects of these open questions by reviewing the relevant recent literature and by analyzing measured data. To this end, we used the Scopus and IEEE Xplore databases and focused on papers that study the effects of the COVID-19 pandemic on electric power grids. The main keywords we used are detailed in Table 3. The search was also restricted to the fields title, abstract, and keywords. In addition, to complement data and ideas from the literature and to demonstrate some of the discussed challenges, we study measured data from both the Israeli power system operator and the European ENTSO-E Transparency Platform [20] and present meaningful patterns of electricity generation and demand, frequency deviations, and load forecasting. The latter was done in cooperation with the Israeli TSO. We hope that this paper will trigger fruitful discussions and encourage further research on these important emerging topics.

The paper continues as follows. Section 2 discusses the effects of the pandemic on energy consumption and renewable share, Section 3 discusses power system planning in light of global pandemics, Section 4 discusses decision support tools for system operators during pandemics, and Section 5 concludes the paper.

**Table 1.** Summary of works focusing on the impacts of COVID-19 on energy systems and markets.

Ref.	Work Focus	Study Region	Challenges
[4]	electricity demand and supply	USA: New York, California, and Florida	system operation, demand and demand ramp rate, load forecasting
[21]	energy sovereignty	regions in the USA and Canada	energy policies
[22]	energy use and home energy management	New York, USA	peak demand and demand ramp rate, energy market/prices
[23]	energy security	regions in the USA	energy policies
[24]	bulk power systems market operation	New York, USA	energy market/prices, load forecasting, energy policies
[25]	electric grid operation	regions in the USA and Europe	system operation challenges, system maintenance, peak demand and demand ramp rate, stability issue
[15]	load forecasting using mobility	regions in the USA and Europe	load forecasting, peak demand and demand ramp rate
[9]	electricity demand trend	Ontario, Canada	peak demand and demand ramp rate, load forecasting, energy market/prices
[26]	power system operation	Saskatchewan, Canada	system operators, load forecasting, stability
[8]	electricity load changes - statistical analysis	Brazil	peak demand and demand ramp rate, load forecasting, energy market
[27]	household energy use	China	energy market/prices, energy policies
[5]	electricity demand, economy and climate	China	system operators, peak demand and demand ramp rate, energy market/prices
[28]	the impact of the lockdown on power generation and load	China	system maintenance, energy market
[29]	photo-voltaic industry's grid parity	China	photo-voltaic forecasting, market/prices, energy policies
[12]	operation of small power grids	Israel, Estonia and Finland	system operators, system maintenance, voltage violation, peak demand and demand ramp rate, stability
[6]	electricity industry and bulk power system	Italy	energy market/prices, voltage violation
[30]	electricity market with large renewables	Italy	peak demand and demand ramp rate, energy market/prices
[31]	electricity consumption	regions in Europe	peak demand and demand ramp rate, system maintenance
[11]	sustainable electricity and mobility	Finland and Sweden	energy market/prices, energy policies, expansion of power system
[32]	people's behavior and residential energy sector sustainability	Kragujevac, Republic of Serbia	energy market/prices
[7]	electricity demand during pandemic	Spain	peak demand and demand ramp rate, energy market/prices, energy policies
[33]	immediate Impacts on the power sector	Europe	peak demand and demand ramp rate, energy market/prices, energy policies, system operators
[34]	electricity distribution system	India	system operators, voltage violation, stability, energy market/prices
[10]	energy consumption	India	energy policies
[35]	power sector operation	India	system operators, voltage violation, peak demand and demand ramp rate
[19]	energy industry	African continent	energy policies, expansion of power systems
[36]	energy access	African continent	energy policies, expansion of power systems
[37]	impacts caused by the falling consumption and demand in the electricity sector.	South Africa	peak demand, energy market
[3]	electricity demand and power system operation	USA, China, Italy, Japan, UK and Brazil	system operators, system maintenance, voltage violation, peak demand and demand ramp rate, energy market/prices
[18]	energy and AI technologies	USA, China, Germany and India	stability, load forecasting, energy market/prices
[2]	electricity industry	worldwide	system operators, voltage violation, load forecasting, energy market/prices
[16]	renewable energy	worldwide	energy policies
[38]	plastic waste, energy and environment	worldwide	energy market/prices, energy policies
[39]	energy demand and consumption	worldwide	peak demand and demand ramp rate, energy market/prices, energy policies

**Table 2.** Works sorted by continent and country.

Continent	References	Countries
North America	[3,4,9,15,18,21–26,39]	USA, Canada
South America	[3,8]	Brazil
Europe	[3,6,7,11,12,18,30,32,33,39]	Italy, France, Germany, Spain
Asia	[3,5,10,18,27–29,34,35,39]	China, India, Japan
Africa	[19,36,37,39]	South Africa
Australia	[40]	

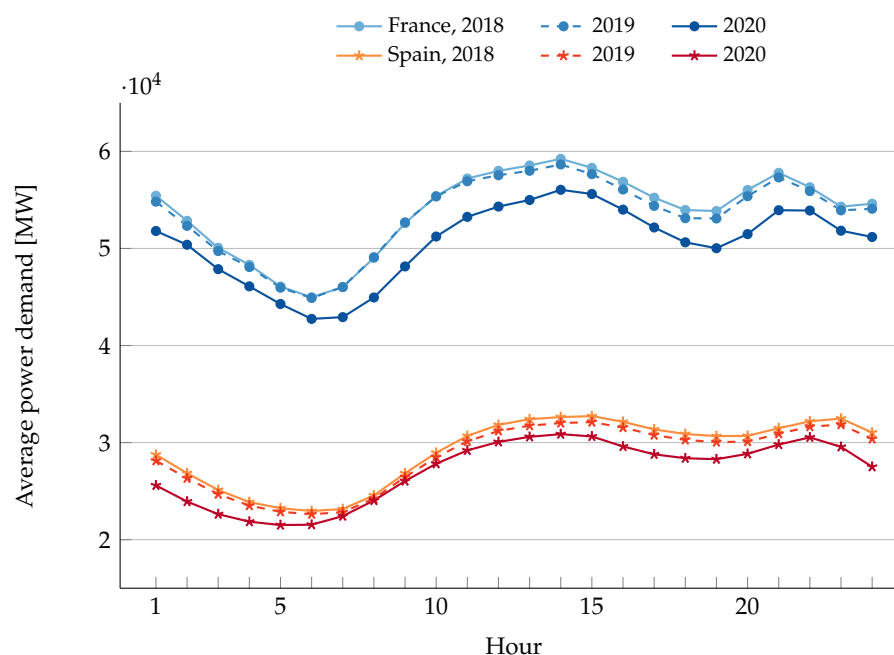
**Table 3.** Search expressions that were used in the literature review. Note that the asterisk is used as a wild-card, allowing the search-engine to capture multiple variations of a word.

Primary Expression	Secondary Expression
	“(power OR energy OR electricity) AND (consumption OR demand)”
	“power system operator * OR transmission system operator *”
“COVID-19 OR coronavirus”	“energy market OR energy price * OR electricity price *”
	“(voltage OR frequency) AND (violation OR regulation OR deviation)”
	“load forecast* OR energy forecast *”

## 2. Effects of the Pandemic on Integration of Renewable Energy Sources

The reduced electricity consumption observed during the pandemic is mainly the result of government measures against the virus spread. In general, when policies to mitigate the pandemic became more severe, the consumption of electricity decreased. Two examples are shown in Figure 1 and Table 4. Figure 1 shows an example of the total daily average demand [MW] in France and Spain in 2018–2020. As can be seen in the figure, the demand in 2020 was considerably lower than in previous years. Table 4 presents the total energy demand and the maximum power demand in Israel during the nine–six weeks before, during and after the first lockdown (March–May 2020) and three weeks before and during the second lockdown (September–October 2020). The table shows that during the first and second lockdowns in Israel there was a decrease in both the energy and the maximum power demand and that as measurements got more severe during both lockdowns, demand further decreased. Moreover, we may clearly see that the measured metrics returned to their normal values as before the lockdown, indicating that the system recovered once governmental measures were relaxed. One direct result of the reduced consumption is an increased relative share of renewable sources in the energy mix. A possible explanation for this effect is that renewable sources are often prioritized over conventional power plants, and as a result their relative share increases when the consumption is low [12]. These phenomena can be seen in Figure 2, which presents the relative share of renewable energy in Israel in each of its lockdowns during 2020. As can be seen, the share of renewable energy increased during all three lockdowns. An exception to this trend is the third lockdown, in which the renewable share decreased towards its end, probably because it occurred during cloudy weather and was also lighter than the previous lockdowns. On the other hand, the first lockdown was the strictest and also occurred during the spring, when conditions for solar generation in Israel are optimal, thus the share of renewable energy was the highest. In fact, during this lockdown the renewable energy share reached new record highs. This is demonstrated in Figure 3, which

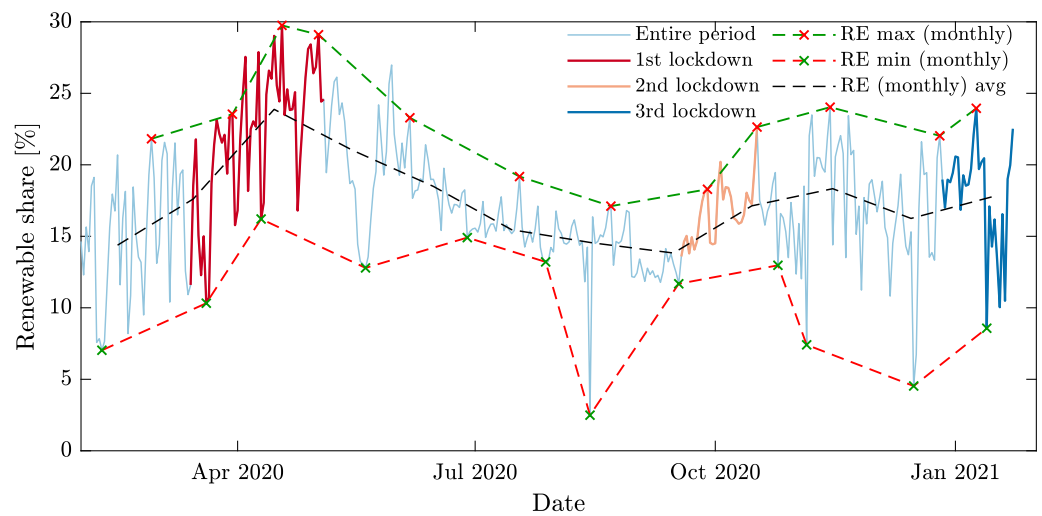
presents the maximal share of renewable energy before and during the first lockdown. Before the pandemic the maximum share of renewable energy was 21.9%, but on 5 April the solar share reached 27% of the total generation, which was the maximum share of renewable energy ever measured in Israel. This record was broken again on 15 April, in which the solar share reached 29%. A similar effect was observed in many different countries [2,3,6,30], so a high share of renewable energy during the pandemic may be considered a global trend.



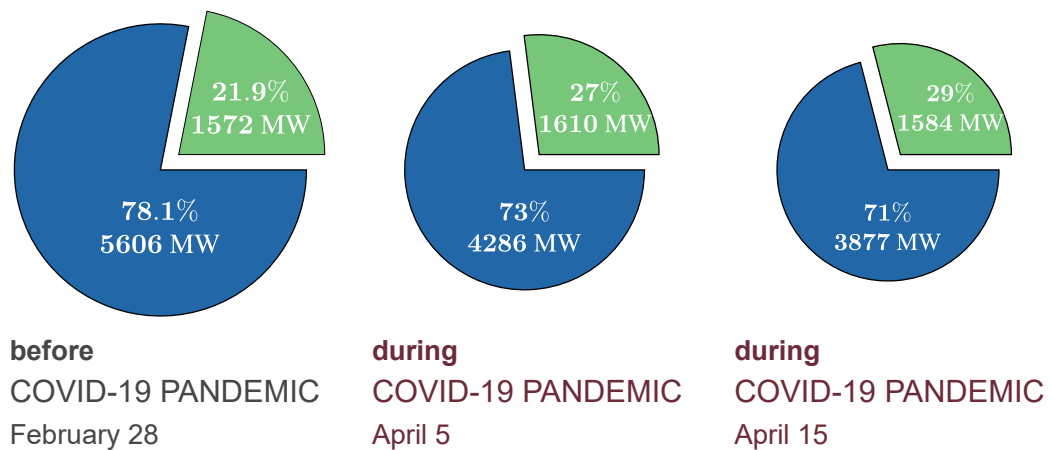
**Figure 1.** Comparison of the total daily average demand [MW] for 2018, 2019, and 2020 in France and Spain.

**Table 4.** Total energy demand [MWh] and maximum power demand [MW] before/during/after the COVID-19 lockdowns in Israel, 2020.

Week	Total Energy Demand [MWh]	Maximum Power Demand [MW]
02–08/03 (before 1st lockdown)	1,253,098	9166
23–29/03 (during 1st lockdown)	1,132,269	8494
30/03–05/04 (during 1st lockdown)	1,079,406	7946
27/04–03/05 (during 1st lockdown)	1,035,383	7294
04/05–10/05 (end of the 1st lockdown)	1,093,062	7559
11/05–17/05 (after 1st lockdown)	1,293,681	9232
14/09–20/09 (before 2nd lockdown)	1,744,541	12,725
21/09–27/09 (during 2nd lockdown)	1,532,869	11,051
28/09–4/10 (during 2nd lockdown)	1,468,051	10,627



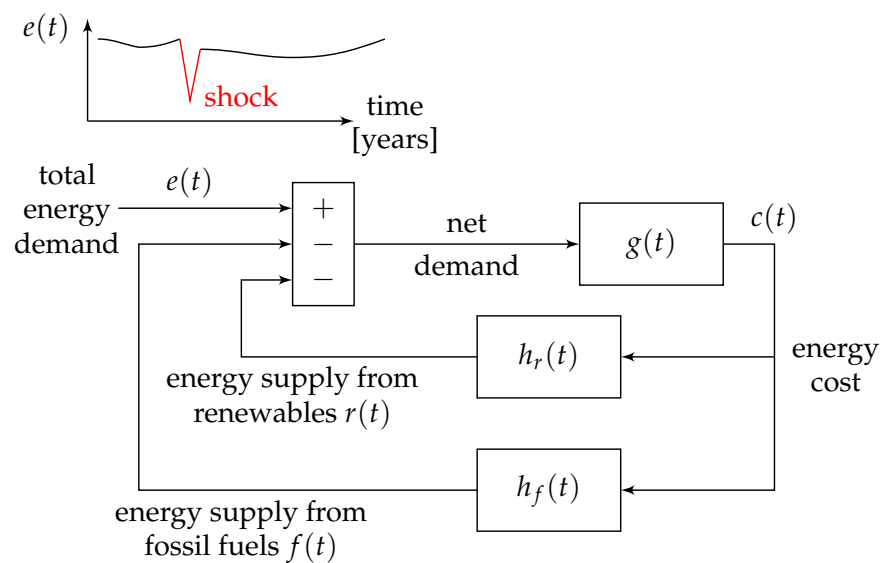
**Figure 2.** Renewable energy (RE) share (mainly solar) in Israel from 1 February 2020 to 23 January 2021.



**Figure 3.** Maximum share of renewable energy in Israel before and during the first lockdown (2020), as a fraction of total generation.

In this context, how will the COVID-19 pandemic, and maybe other future pandemics, affect the integration of renewable energy sources in the long-term? A unique idea that may shed light on this question is the one of “economic shocks” [11,16,19,36]. According to this idea, if the integration of renewable sources can be described as a dynamic system operating on time-scales of years, then several months of low consumption may be viewed as a negative impulse signal (a shock), which causes reactions and counter-reactions that evolve in a closed feedback loop. In other words, the dynamic system describing the long-term integration of renewable sources is responding to an “economic shock”—an impulse signal that models a period of low energy consumption. An illustrative example is shown in Figure 4. In this model,  $e(t)$  is the total energy demand;  $c(t)$  is the cost of energy;  $r(t)$  is the energy supply from renewable sources;  $f(t)$  is the energy supply from fossil fuels; and  $g(t)$ ,  $h_r(t)$ , and  $h_f(t)$  are linear and time-invariant systems that links these signals to each other.





**Figure 4.** An illustrative feedback system describing the effects of “economic shocks”: periods of low consumption are modeled as negative impulse signals, which cause reactions and counter-reactions that evolve in a closed feedback loop.

Here are two intuitions for dynamic interactions that may be triggered by such shocks. On one hand, economic shocks may *slow down* the integration of renewable sources, simply because weaker economies cannot allocate enough resources to sustain such development [36]. More specifically, the COVID-19 pandemic has already undermined renewable energy policies, which are under question even at normal times [16], thus delaying the deployment of renewable energy systems. On the other hand, it is also possible that the pandemic will eventually help *promote* the long-term integration of renewable energy sources, due to its negative effect on fossil fuel prices. During the pandemic, less fossil fuels have been used, which led to variations in these fuels prices (an “economic shock”). As fossil fuels production require large-scale investments in infrastructure, and such investments are questionable in periods of uncertainty, the pandemic may eventually trigger a domino effect (feedback) that may eventually enhance the integration of renewable energy sources [16].

Which of these two opposing trends will eventually prove to be more dominant? Suppose that we will see a series of economic shocks, being pandemic- or climate change-related, will they increase or decrease the use of renewable energy sources? What policies can be implemented now to support continuing integration of such sources, in spite of future economic shocks? While at the present time we simply do not know the answers, perhaps a clever dynamic modeling may shed new light on this complex problem.

Another result of the pandemic is that it provides a glance into a renewable-rich future, because, as discussed above, exceptionally low consumption leads to high share of renewable sources. An interesting question is therefore what can we learn from these periods of low consumption about renewable-rich power systems? Perhaps a few clues can be obtained by inspecting fluctuations in wholesale energy market prices, as they reflect in the recent literature. One recent work [2] shows that during lockdowns prices in Europe decreased dramatically, to less than half of the average price during the same period in previous years [2], and similar effects were reported in the U.S. [3] and India [34]. In addition, the authors of [6] study the impact of the pandemic on Italy’s electricity consumption, wholesale electricity market, and ancillary services, concluding that while the Italian power system can run conveniently with a high share of renewable energy, the required ancillary services have a significant cost. The work in [30] supports this view, and shows that the lockdown in Italy resulted in a 103% increment in the cost of re-dispatch,

when compared to the same period in previous years. The reason in this case is almost certainly the reduced consumption and the increased share of renewables.

Are these effects transitional in nature, or do they reflect real problems associated with renewable energy integration on a large-scale? As above, while currently we do not know the answer, perhaps clever dynamic modeling of energy-related economic processes can prove to be a viable research tool.

Last in this section, but not least, are problems that relate to frequency stability. In times of low consumption, or when renewable energy generation is high, fewer conventional power plants are operated, which leads to less spinning reserve and lower rotational inertia [41]. As a result, the frequency becomes less stable, and may deviate sharply following a loss of a generation unit, a fault, or a fast change in renewable energy production. The COVID-19 pandemic, again serving here as a large-scale experiment in renewable-rich power systems, demonstrated the severity of these effects. As an example, the effects of the pandemic on the frequency of the Israeli grid are summarized in Table 5. The table presents the number of seconds in which the frequency deviated from its nominal value during each week, for six weeks in March, April, and May, 2020. During all weeks reported the average temperature and cloudiness were similar, to mitigate the effects of varying weather conditions. In the table, frequency deviations are divided to higher and lower than 100 mHz or 200 mHz. The main conclusion from the data is that the overall duration of high frequency deviations increased during the lockdown and decreased back to normal values when the lockdown was over. This can be explained by the decrease in consumption, which raised the relative share of solar generation in Israel, as can be seen in Figures 2 and 3, and led to reduced rotational inertia. There is good reason to believe that such effects are global, so data recorded during the pandemic can be used as a research tool to better understand the frequency stability of future renewable-rich systems.

**Table 5.** Duration [in sec] of frequency deviations [in Hz] before and during the COVID-19 first lockdown in Israel, March–May 2020.

Week	<49.8	[49.8, 49.9]	(50.1, 50.2]	>50.2
02–08/03 (before 1st lockdown)	0	801	2195	32
23–29/03 (during 1st lockdown)	20	1612	2903	13
30/03–05/04 (during 1st lockdown)	128	4245	3716	667
27/04–03/05 (during 1st lockdown)	24	580	1805	22
04/05–10/05 (end of the 1st lockdown)	7	810	871	0
11/05–17/05 (after 1st lockdown)	7	57	1547	0

### 3. Expansion of Power Systems in Light of the COVID-19 Pandemic

Should the expansion plans of power systems consider the case of severe future pandemics? One reason to think so is the effects of pandemics on load distribution, following the demographic and economical changes they cause. Little evidence for such effects was provided by the COVID-19 pandemic in 2020, as reported in several recent works. During the pandemic people spend more time at home due to social distancing, which generally leads to larger load in the private sector [31]. Nevertheless, in several large cities the load decreased, as people migrated from urban to rural areas [12,42]. Such migration is made possible due to the growing trend of working and studying from home, and can be explained as a way of seeking refuge from populated areas, or a mean to reduce the cost of living in such difficult economic times [43]. These changes, in addition to uncertain load predictions in the industrial and business sectors [12], lead not only to a reduction in the total load, but also to very different geographical distribution of the same load. In this light, should additional transmission lines be placed in rural areas that may become more populated? Should distribution networks be upgraded in domestic areas as more people work from home? Can current forecasting models still be used for scheduling



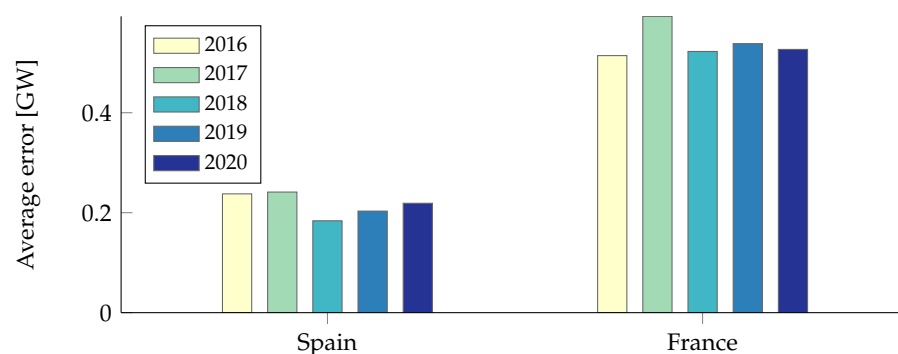
quarterly and yearly maintenance programs? These concerns join many others, and make the power system expansion planning problem even more complex than it already is [44].

Another related question is that of planned interconnections between neighboring grids. As discussed above, periods of low consumption undermine the stability of power systems, as less conventional units are being operated. Because larger systems are more immune to single failures, and therefore tend to be more reliable overall, a natural conclusion is that pandemics provide an incentive to interconnect. In this context, should decisions about future interconnections take into account possible global health crises? Past experience shows that stability and reliability by themselves are often not important enough to justify interconnections. Some examples are Israel, Japan, and Texas, which are until this day an “electric island”, despite being relatively small in both area and overall power consumption. Perhaps the risk of pandemics, accompanied by the future rise of renewable energies, will affect this line of thinking. An opposite example is Estonia, whose government recently decided to disconnect from the Russian electric grid in five years. A natural question is what will be the effect of a future pandemic on the Estonian grid and the surrounding Baltic countries after the disconnection.

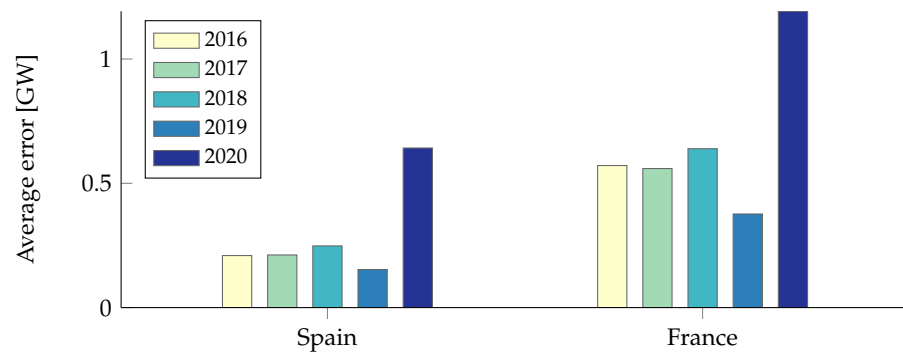
#### 4. Tools to Support System Operators during Global Health Crises

As discussed in [2], system operators worldwide reacted very well to the difficulties caused by the COVID-19 pandemic, and were able to stabilize the system and provide electric energy to all who need it, with very few interruptions. Nevertheless, it was a challenging operation and is expected to become more difficult as the share of renewable energy will increase. Assuming that we will see more acute pandemics in the future, is there a place to consider special decision support tools [18], which may help system operators in times of severe health crises?

Naturally, if such a tool is to be developed, the problem of load forecasting should be at the center of attention. Most load forecasting algorithms receive as inputs the time, weather conditions, and load history, but do not consider socioeconomic changes, and therefore could not operate well during the first lockdown of the COVID-19 pandemic. To emphasize this problem, Figures 5 and 6 present the average daily load forecasting error in Spain and France during 2016–2020. Figure 5 presents data between January 1st and December 31st, excluding March 15th to April 15th, which is the period of the first lockdown, whereas Figure 6 presents data from March 15th to April 15th. Both Spain and France were strongly impacted by the COVID-19 virus spread, and both governments started implementing containment measures in mid-March 2020. As can be seen in Figure 5, excluding the dates of the first lockdown, there was no significant change in the forecasting error when comparing 2020 to previous years. However, Figure 6 shows that in both countries the forecasting error during the lockdown was significantly larger in 2020 in comparison to the same dates in previous years, emphasizing the difficulty in predicting load profiles during health crises, or any other large-scale event that dramatically affects social behavior.

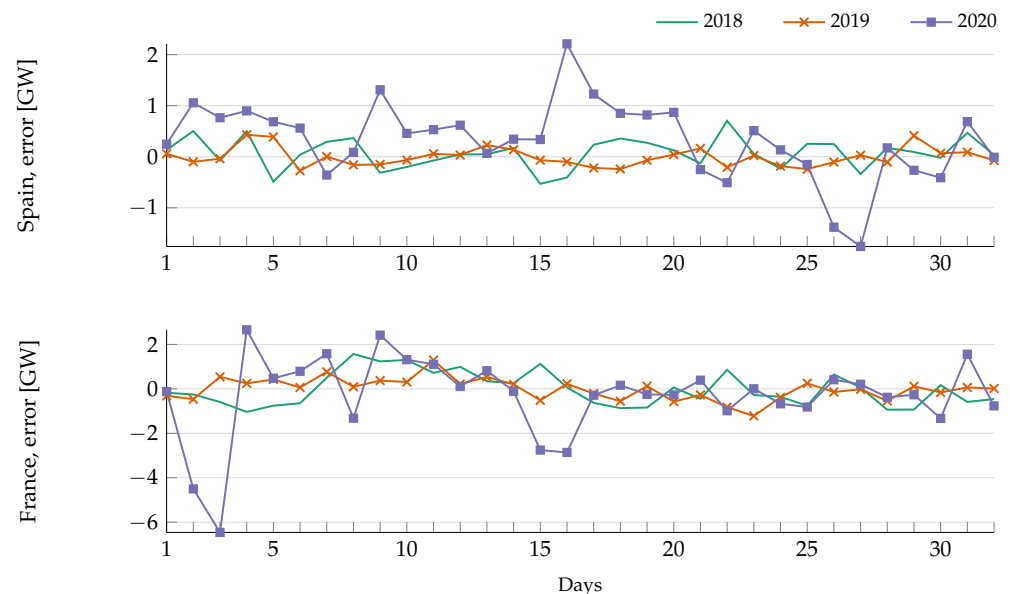


**Figure 5.** Average daily load forecasting error in Spain and France, between 1 January and 31 December, excluding 15 March to 15 April, 2016–2020.



**Figure 6.** Average daily load forecasting error in Spain and France, between 15 March and 15 April, 2016–2020.

A different presentation of the same data can be seen in Figure 7, which shows the forecasting error in Spain and France between 15th March and 15th April in 2018–2020. The error is calculated as the difference between the daily average forecast and the actual load, and is presented in absolute values.



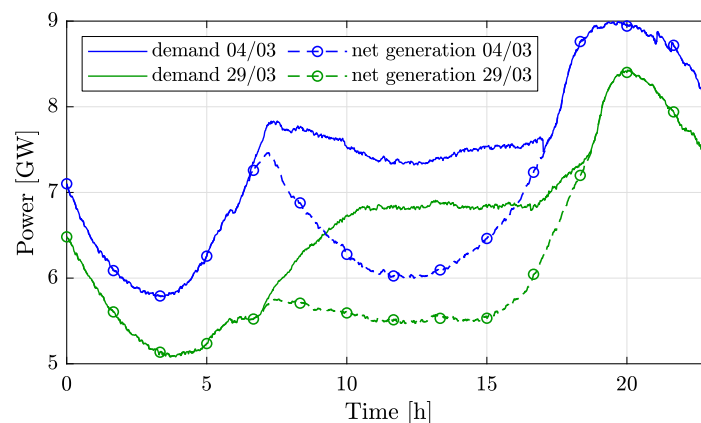
**Figure 7.** Load forecasting error in Spain and France between 15 March and 15 April in 2018–2020.

Another evidence for the same idea is shown in [5], where a neural network model is developed to analyze the impacts of COVID-19 on the electricity and petroleum demand in China. It is concluded that previous forecasting models that use historical trends are now inaccurate, due to the unpredictable human element embedded in global pandemics. On the other hand, it is important to note that the industry is well aware of this difficulty, and overall was able to provide first-order solutions which worked quite well [2]. For example, several utilities modified weekday forecasts to follow consumption patterns of weekends or holidays, thus providing a simple first-order solution to the problem above. Other utilities adjusted their forecasting models so that they would anticipate lower demand profiles, and asked for factories and commercial buildings to update in advance on any major changes in consumption. A more sophisticated solution has been proposed in [15], which suggests improving the forecasting by using mobility data to identify load changes caused by socioeconomic behaviors and governmental restrictions. It is most likely that this and other sophisticated forecasting methods will be needed to solve this important problem.

Another challenge to system operators which is caused by the reduced consumption is voltage deviations [2,12,34]. This is mostly due to shunt capacitance in transmission lines,

that generate reactive power. When the overall consumption is low, this reactive power changes the power flow in the network, and may result in increased voltage amplitudes, i.e., the Ferranti effect. The issue of voltage stability was especially problematic in areas with factories and commercial buildings that were closed during the pandemic [3]. Usually, this problem is solved by operating synchronous machines in an under-excited mode, in which they absorb reactive power. However, when less conventional power plants are being used, this voltage control mechanism may be less effective. Another solution is to switch transmission lines on and off [2], as was done by utility companies in Asia and North America during the first few months of the pandemic. Can special-purpose algorithms help system operators decide on such actions in real-time? While such algorithms are probably not in high demand today, perhaps they will be needed during future periods of especially low consumption.

An additional challenge to system operators during periods of low consumption is increased ramp rates of conventional power (the infamous “duck curve”), which may lead to reduced reliability, poor resiliency, and non-optimal economic dispatch [12]. To demonstrate this, Figure 8 compares the overall demand and conventional generation in Israel during 24 hours in both March 4 and 29, 2020 (before and during the lockdown). As seen in the graph, the ramp rate of conventional generation between 15:00 and 20:00 on the 29th is significantly higher, with an increase of approximately 2900 MW, which was 34% of the peak conventional generation on that day, in comparison to an increase of about 2500 MW on the 4th, which was 27% of the peak conventional generation. Similar effects are reported in [6], which presents demand patterns in Italy during March 2020, and in [4], which examines the pandemic’s impact on the demand in New York, California, and Florida using a simple linear regression model. Peak demand and ramp rate were identified in this last work as the main variables that contribute to the stress on the grid. It is possible that in the future special decision making tools may help system operators deal with these effects, perhaps by engaging fast-reacting units such as renewable sources or storage devices.



**Figure 8.** Comparison of the total demand and conventional generation in Israel during 24 h on two sunny days: 4 March and 29 March 2020.

## 5. Conclusions

Power systems have been going through a transitional change in the last few years, with the integration of new technologies such as electric vehicles, storage devices, and renewable energy sources. In the midst of this change, the COVID-19 pandemic triggered socioeconomic phenomena that led to very different patterns of energy consumption, and by doing so emphasized the most crucial problems of this global transition. The current paper focuses on three such problems: the effects of the pandemic on the integration of renewable sources, its possible effects on expansion planning problems, and the technical difficulties faced by system operators. The mentioned open questions concerning the long-term operation and planning of power systems under the effect of the pandemic are

summarized in Table 6. A key question is how the pandemic will influence the global transition to a low-carbon economy and, in particular, the integration of renewable energy sources. This question has two aspects: one of policy, the other of economy. With regard to policy, the pandemic caused a decrease in consumption, which raised the relative share of renewable sources in the energy mix, and provided us a glance into a renewable rich future. Therefore, the question is how policy-makers will react to evidence from the field. On the one hand, the high share of renewables revealed to be challenging, as it led to low inertia, reduced frequency, voltage instability, “duck curve” effects, and fluctuating prices. On the other hand, although the renewable share increased, system operators worldwide were able to manage it without major failures. As for the economic aspect of this question, the pandemic damaged both the fossil fuel industry and the ability of many governments to continue supporting the renewable energy industry, and so it is currently unclear how these industries will recover. To understand the impact of the COVID-19 on renewables under different policy schemes, there is a need for a sophisticated dynamic model that will capture to relationship between energy demand, energy prices and generation of both fossil fuels and renewables. Another important question is how the pandemic affects current power system expansion plans. Evidence shows that the pandemic did not only cause a reduction in electricity load, but also a load shift from the industrial and commercial sectors to the private sector, and from large cities to peripheral settlements. Therefore, there is place for clever load forecasting models that will take into account changes in both social and demographic behavior. This may trigger and update current expansion plans, with accordance to the expected changes. Moreover, due to the many technical difficulties that electric grids experienced during the pandemic, there is a need to assess the vulnerability of small electric grids to global health crises and an increasing share of renewable energy. The last but not least major question we investigate in this paper is the need for decision supporting tools for system operators in times of abnormal consumption. We show that during lockdowns there was a significant increase in frequency deviations and load forecasting errors. Perhaps advanced models, for instance, machine learning-based algorithms, may assist system operators during crises. For example, novel solutions may use new sources of data, such as mobility data, national health status, and governmental restrictions, to forecast the expected demand in the short-term, and point out the optimal network topology or generation dispatch. A central idea in this work is that the pandemic is a large-scale socioeconomic phenomenon, and as such reveals new data that may help the community to better understand the power systems of tomorrow. The pandemic, with all its difficulties and problems, provided the power system community priceless data, which should be exploited for further research.

**Table 6.** Summary of open questions and challenges.

Category	Open Questions and Challenges
Renewable energy integration	<ul style="list-style-type: none"> <li>✓ How will the pandemic affect the energy mix in the long-term, and specifically the integration of renewable energy sources?</li> <li>✓ Suppose that we will see a series of economic shocks, be them pandemic or climate change-related, will they increase or decrease the use of renewable energy sources?</li> <li>✓ What will be the consequences for frequency stability?</li> <li>✓ What policies can be implemented now to support continuing integration of such sources, in spite of future economic shocks?</li> </ul>
System expansion planning	<ul style="list-style-type: none"> <li>✓ Should current power system expansion plans change in light of the COVID-19 pandemic?</li> <li>✓ Should additional transmission lines be placed in rural areas that may become more populated?</li> <li>✓ Should distribution networks be upgraded in domestic areas as more people work from home?</li> <li>✓ Can current forecasting models still be used for scheduling quarterly and yearly maintenance programs?</li> <li>✓ Should decisions about future interconnections take into account possible global health crises?</li> </ul>
System operation	<ul style="list-style-type: none"> <li>✓ Which new tools should be provided to support system operators during crises?</li> <li>✓ Can special-purpose real-time algorithms help system operators decide on the optimal topology for voltage stability and the optimal generation unit dispatch for frequency regulation?</li> </ul>

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## Abbreviations

The following abbreviations are used in this manuscript:

COVID-19	Coronavirus disease 2019
ENTSO-E	European Network of Transmission System Operators for Electricity
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
TSO	Transmission system operator

## References

- World Health Organization. Statement on the Second Meeting of the International Health Regulations (2005) Emergency Committee Regarding the Outbreak of Novel Coronavirus (2019-nCoV), 2020. Available online: <https://www.who.int/news-room/detail/30-01-2020-statement-on-the-second-meeting-of-the-international-health-regulations-> (accessed on 10 September 2020).
- Paaso, A.; Bahramirad, S.; Beerten, J.; Bernabeu, E.; Chiu, B.; Enayati, B.; Hederman, B.; Jones, L.; Jun, Y.; Koch, H.; et al. Sharing Knowledge on Electrical Energy Industry’s First Response to COVID-19. Technical Report, Industry Technical Support Leadership Committee, 2020. Available online: [https://resourcecenter.ieee-pes.org/technical-publications/white-paper/PES\\_TP\\_COVID19\\_050120.html](https://resourcecenter.ieee-pes.org/technical-publications/white-paper/PES_TP_COVID19_050120.html) (accessed on 29 October 2020).
- Zhong, H.; Tan, Z.; He, Y.; Xie, L.; Kang, C. Implications of COVID-19 for the electricity industry: A comprehensive review. *CSEE J. Power Energy Syst.* **2020**, *6*, 489–495.
- Agdas, D.; Barooah, P. The COVID-19 pandemic’s impact on U.S. electricity demand and supply: An early view from the data. *IEEE Access* **2020**, *8*, 151523–151534. [[CrossRef](#)]
- Norouzi, N.; de Rubens, G.Z.; Choupanpiesheh, S.; Enevoldsen, P. When pandemics impact economies and climate change: Exploring the impacts of COVID-19 on oil and electricity demand in China. *Energy Res. Soc. Sci.* **2020**, *68*, 101654. [[CrossRef](#)]
- Ghiani, E.; Galici, M.; Mureddu, M.; Pilo, F. Impact on electricity consumption and market pricing of energy and ancillary services during pandemic of COVID-19 in Italy. *Energies* **2020**, *13*, 3357. [[CrossRef](#)]
- Santiago, I.; Moreno-Munoz, A.; Quintero-Jiménez, P.; Garcia-Torres, F.; Gonzalez-Redondo, M. Electricity demand during pandemic times: The case of the COVID-19 in Spain. *Energy Policy* **2021**, *148*, 111964. [[CrossRef](#)] [[PubMed](#)]
- de Mello Delgado, D.B.; de Lima, K.M.; de Camargo Cancela, M.; dos Santos Siqueira, C.A.; Carvalho, M.; de Souza, D.L.B. Trend analyses of electricity load changes in Brazil due to COVID-19 shutdowns. *Electr. Power Syst. Res.* **2021**, *193*, 107009. [[CrossRef](#)]
- Abu-Rayash, A.; Dincer, I. Analysis of the electricity demand trends amidst the COVID-19 coronavirus pandemic. *Energy Res. Soc. Sci.* **2020**, *68*, 101682. [[CrossRef](#)]
- Aruga, K.; Islam, M.M.; Jannat, A. Effects of COVID-19 on Indian energy consumption. *Sustainability* **2020**, *12*, 5616. [[CrossRef](#)]
- Kanda, W.; Kivimaa, P. What opportunities could the COVID-19 outbreak offer for sustainability transitions research on electricity and mobility? *Energy Res. Soc. Sci.* **2020**, *68*, 101666. [[CrossRef](#)] [[PubMed](#)]
- Carmon, D.; Navon, A.; Machlev, R.; Belikov, J.; Levron, Y. Readiness of Small Energy Markets and Electric Power Grids to Global Health Crises: Lessons From the COVID-19 Pandemic. *IEEE Access* **2020**, *8*, 127234–127243. [[CrossRef](#)]
- Biol, F. The Coronavirus Crisis Reminds us that Electricity is More Indispensable than Ever, 2020. Available online: <https://www.iea.org/commentaries/the-coronavirus-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever> (accessed on 10 September 2020).
- Bhagwat, P. Identifying Impacts of COVID-19 on the Indian Power Sector, 2020. Available online: <https://fsr.eui.eu/identifying-impacts-of-covid-19-on-the-indian-power-sector/> (accessed on 10 September 2020).
- Chen, Y.; Yang, W.; Zhang, B. *Using Mobility for Electrical Load Forecasting during the COVID-19 Pandemic*; arXiv: Washington, WA, USA, 2020.
- Hosseini, S.E. An outlook on the global development of renewable and sustainable energy at the time of COVID-19. *Energy Res. Soc. Sci.* **2020**, *68*, 101633. [[CrossRef](#)] [[PubMed](#)]
- Henry, M.S.; Bazilian, M.D.; Markuson, C. Just transitions: Histories and futures in a post-COVID world. *Energy Res. Soc. Sci.* **2020**, *68*, 101668. [[CrossRef](#)]
- Wang, B.; Yang, Z.; Xuan, J.; Jiao, K. Crises and opportunities in terms of energy and AI technologies during the COVID-19 pandemic. *Energy AI* **2020**, *1*, 100013. [[CrossRef](#)]



19. Akrofi, M.M.; Antwi, S.H. COVID-19 energy sector responses in Africa: A review of preliminary government interventions. *Energy Res. Soc. Sci.* **2020**, *68*, 101681. [CrossRef]
20. ENTSO-E. Transparency Platform, 2020. Available online: <https://transparency.entsoe.eu/> (accessed on 25 October 2020).
21. Brosemer, K.; Schelly, C.; Gagnon, V.; Arola, K.L.; Pearce, J.M.; Bessette, D.; Olabisi, L.S. The energy crises revealed by COVID: Intersections of indigeneity, inequity, and health. *Energy Res. Soc. Sci.* **2020**, *68*, 101661. [CrossRef]
22. Chen, C.F.; de Rubens, G.Z.; Xu, X.; Li, J. Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19. *Energy Res. Soc. Sci.* **2020**, *68*, 101688. [CrossRef]
23. Graff, M.; Carley, S. COVID-19 assistance needs to target energy insecurity. *Nat. Energy* **2020**, *5*, 352–354. [CrossRef]
24. Ruan, G.; Wu, J.; Zhong, H.; X, Q.; Xie, L. Quantitative Assessment of U.S. Bulk Power Systems and Market Operations during the COVID-19 Pandemic, 2020. Available online: [https://www.researchgate.net/profile/Guangchun\\_Ruan/publication/343878490\\_Quantitative\\_Assessment\\_of\\_US\\_Bulk\\_Power\\_Systems\\_and\\_Market\\_Operations\\_during\\_the\\_COVID-19\\_Pandemic/links/5f460a0ba6fdcccc4306861f/Quantitative-Assessment-of-US-Bulk-Power-Systems-and-Market-Operations-during-the-COVID-19-Pandemic.pdf](https://www.researchgate.net/profile/Guangchun_Ruan/publication/343878490_Quantitative_Assessment_of_US_Bulk_Power_Systems_and_Market_Operations_during_the_COVID-19_Pandemic/links/5f460a0ba6fdcccc4306861f/Quantitative-Assessment-of-US-Bulk-Power-Systems-and-Market-Operations-during-the-COVID-19-Pandemic.pdf) (accessed on 15 December 2020).
25. Noorazar, H.; Srivastava, A.K.; Sajan, K.S.; Pannala, S. *Data-Driven Operation of the Resilient Electric Grid: A Case of COVID-19*; arXiv: Washington, WA, USA, 2020.
26. Safari, N.; Price, G.; Chung, C. Comprehensive assessment of COVID-19 impact on Saskatchewan power system operations. *IET Gener. Transm. Distrib.* **2020**, *15*, 164–175. [CrossRef]
27. Cheshmehzangia, A. COVID-19 and household energy implications: what are the main impacts on energy use? *Heliyon* **2020**, *6*, e05202. [CrossRef]
28. Lu, Y.; Zhou, R.; Wang, J. Analysis of Power Generation and Load Change Under the Influence of Lockdown Based on COVID-19 Epidemic. In Proceedings of the 2020 AEIT International Annual Conference (AEIT), Catania, Italy, 23–25 September 2020; [CrossRef]
29. Song, Y.; Liu, T.; Li, Y.; Ye, B. The influence of COVID-19 on grid parity of China’s photovoltaic industry. *Environ. Geochem. Health* **2020**. [CrossRef]
30. Graf, C.; Quagliay, F.; Wolakz, F.A. Learning about electricity market performance with a large share of renewables from the COVID-19 lock-down. *Program Energy Sustain. Dev.* **2020**, 1–21.
31. Bahmanyar, A.; Estebansari, A.; Ernst, D. The impact of different COVID-19 containment measures on electricity consumption in Europe. *Energy Res. Soc. Sci.* **2020**, *68*, 101683. [CrossRef] [PubMed]
32. Cvetković, D.; Nešović, A.; Terzić, I. Impact of people’s behavior on the energy sustainability of the residential sector in emergency situations caused by COVID-19. *Energy Build.* **2021**, *230*, 110532. [CrossRef]
33. Bompard, E.; Mosca, C.; Colella, P.; Antonopoulos, G.; Fulli, G.; Masera, M.; Poncela-Blanco, M.; Vitiello, S. The Immediate Impacts of COVID-19 on European Electricity Systems: A First Assessment and Lessons Learned. *Energies* **2020**, *14*, 96. [CrossRef]
34. Murty, V.V.S.N.; Sharma, A.K. Impact of COVID-19 pandemic on Indian electrical distribution system. *Int. J. Comput. Digit. Syst.* **2020**, *10*, 1–8.
35. Elavarasan, R.M.; Shafiullah, G.M.; Raju, K.; Mudgal, V.; Arif, M.T.; Jamal, T.; Subramanian, S.; Balaguru, V.S.S.; Reddy, K.S.; Subramaniam, U. COVID-19: Impact analysis and recommendations for power sector operation. *Appl. Energy* **2020**, *279*, 115739. [CrossRef]
36. Gebreslassie, M.G. COVID-19 and energy access: An opportunity or a challenge for the African continent? *Energy Res. Soc. Sci.* **2020**, *68*, 101677. [CrossRef]
37. Andrade, J.V.B.; Salles, R.S.; Silva, M.N.S.; Bonatto, B.D. Falling Consumption and Demand for Electricity in South Africa-A Blessing and a Curse. In Proceedings of the 2020 IEEE PES/IAS PowerAfrica, Nairobi, Kenya, 15–18 August 2020. [CrossRef]
38. Klemeš, J.J.; Fan, Y.V.; Tan, R.R.; Jiang, P. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109883. [CrossRef]
39. Jiang, P.; Fan, Y.V.; Klemeš, J.J. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Appl. Energy* **2021**, *285*, 116441. [CrossRef]
40. Mastropietro, P.; Rodilla, P.; Battle, C. Emergency measures to protect energy consumers during the Covid-19 pandemic: A global review and critical analysis. *Energy Res. Soc. Sci.* **2020**, *68*, 101678. [CrossRef]
41. Milano, F.; Dörfler, F.; Hug, G.; Hill, D.J.; Verbic, G. Foundations and challenges of low-inertia systems (invited paper). In Proceedings of the Power Systems Computation Conference, Dublin, Ireland, 11–15 June 2018; pp. 1–25.
42. Assembly of European Regions. Rural-Urban Relations in Times of COVID-19, 2020. Available online: <https://aer.eu/rural-urban-relations-in-times-of-covid-19/> (accessed on 9 September 2020).
43. Bick, A.; Blandin, A.; Mertens, K. *Work from Home after the COVID-19 Outbreak*; Technical Report; Federal Reserve Bank of Dallas: Dallas, TX, USA, June 2020.
44. Gorenstin, B.G.; Campodonico, N.M.; Costa, J.P.; Pereira, M.V.F. Power system expansion planning under uncertainty. *IEEE Trans. Power Syst.* **1993**, *8*, 129–136. [CrossRef]