Applied Energy 285 (2021) 116370

Contents lists available at ScienceDirect

Applied Energy

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

How did the German and other European electricity systems react to the COVID-19 pandemic?

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ARTICLE INFO

Keywords:
Electricity system
COVID-19 pandemic
Renewable Energy Sources
Flexibility
Grid stability

ABSTRACT

The first wave of the COVID-19 pandemic led to decreases in electricity demand and a rising share of Renewable Energy Sources in various countries. In Germany, the average proportion of net electricity generation via Renewable Energy Sources rose above 55 % in the first half of 2020, as compared to 47 % for the same period in 2019. Given these altered circumstances, in this paper we analyze how the German and other European electricity systems behaved during the COVID-19 pandemic. We use data visualization and descriptive statistics to evaluate common figures for electricity systems and markets, comparing developments during the COVID-19 pandemic with those of previous years. Our evaluation reveals noticeable changes in electricity consumption, generation, prices, and imports/exports. However, concerning grid stability and ancillary services, we do not observe any irregularities. Discussing the role of various flexibility options during the COVID-19 pandemic, a relatively higher grid capacity resulting from a decreased electricity consumption, in particular, may have contributed to grid stability.

1. Introduction

Countermeasures adopted during the first wave of the COVID-19 pandemic have caused severe shocks to the energy sector [1]. Among others, a significant decline in global demand for oil and gas, along with less flexible extraction of these fuels, has resulted in a decline in oil and gas prices [2]. Oil prices for the West Texas Intermediate (WTI) barrel were negative for the first time in history on April 20, 2020 [3]. Assessing the electricity system, the authors in [4] and the International Energy Agency point out that electricity consumption fell in many countries. Such shocks ultimately led to different short-term effects that affected electricity systems worldwide [5]. For instance, a decrease in electricity demand often implied that the share of Renewable Energy Sources (RES) actually increased.

Newly available are first scientific publications focusing on both the effects of COVID-19 on the electricity system and the importance of well-functioning electricity systems during the COVID-19 pandemic. For instance, [6] analyze the impact of containment measures on the electricity consumption of six European countries. [7] take a view on different energy sectors by analyzing cross-domain data, e. g., mobile device location and satellite imaging data. [8] investigate the impact of COVID-19 on socio-economic and technical issues faced by utilities making a case study on the Indian power system. With regard to sustainability, [9,10], and [11] analyze the effects of COVID-19 on CO_2 emission reductions. [12] investigate the relationship between air pollution and COVID-19 related deaths. [10] evaluate short-term reductions in CO_2 emissions with respect to the long-term impact on innovation in clean energy. The authors find that, as a result of a stressed budget and a suffering industrial sector, climate change mitigation targets have been relaxed and renewable energy investments may be postponed. In addition, [13] review current governmental interventions in Africa and argue that governments should prioritize RES in their economic recovery plans. Similarly, [14] identify a general need to create incentives for new investments in clean energy. [4] and [15] assess whether policy focus on sustainability has been reduced and examine lessons learned about decarbonizing transport.

While the environmental sustainability of an electricity system is a critical topic, an increased share of RES also affects the electricity system and corresponding markets in terms of various indicators, such as grid stability and prices. The electricity grid is subject to physical laws – e. g., to Kirchhoff's laws: supply and demand must be balanced to ensure an operating frequency within a given technical range and,

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https://doi.org/10.1016/j.apenergy.2020.116370
Received 12 August 2020; Received in revised form 9 November 2020; Accepted 16 November 2020
Available online 6 January 2021

thereby, maintain system stability [16]. Here, the term "flexibility" refers to the ability to manage and address imbalances between electricity supply and demand [17,18]. Historically developed electricity systems that relied on conventional power plants were designed to adapt the timing of electricity generation to largely inflexible demand (patterns). Inelastic demand was mainly based on the requirements of the respective consumers, with the result that conventional power plants shut down or started up when needed [17]. With marginal costs close to zero, wind and solar power plants always generate electricity given appropriate weather conditions, unless they need to be shut down. In Germany, for instance, grid operators enforce such shut downs, which result in a curtailment of wind and solar power plants [19]. These feed-in management measures are necessary to ensure grid stability [19,20]. In other countries, e. g., Denmark, negative electricity prices incentivize operators to shut down wind and solar power plants [20]. A higher share of RES (e. g., in Germany, 55 % in 2020 [21]) leads to less flexibility on the supply side: RES can only offer limited flexibility as it is only possible to lower their feed-in. Various flexibility options are currently available to provide the required flexibility in current and in particular future electricity systems. These options include demand-side flexibility, sector coupling, supply-side flexibility, storages, and grid extensions to balance supply and demand [17,22–24].

As described before, in some electricity systems, the COVID-19 pandemic led to altered circumstances, e. g., a declining electricity demand and a resulting higher share of RES. In literature, there is first work on the impact of increasing shares of RES on electricity systems and corresponding electricity demand. [25] model least-cost options considering an integration of intermittent renewable in power systems and find that flexibility options like demand response can reduce system costs. Investigating long-term projections of Norwegian energy demand, [26] examine the impact of future energy demand on renewable energy production. Taking a look at a Danish future energy scenario, [27] assess the potential of demand response for Denmark as a leading country for high shares in RES. [28] examine the impact of demand response strategies on the penetration of RES for the case of the Flores Island, Azores. Those papers consider circumstances with a high share of RES modeling scenarios of future energy systems on a theoretical basis.

During the COVID-19 pandemic, however, we can study such changes in a real-world electricity system. Furthermore, the altered circumstances may have led to situations in the electricity system for which so far only limited experience and knowledge exists. Therefore, in this paper, we ask the following research question:

How did the German and other European electricity systems react to the COVID-19 pandemic and what was the role of different flexibility options?

We investigate the extent to which relevant indicators of the electricity system and markets have developed during the COVID-19 pandemic with a high share of RES. Furthermore, we discuss the role of different flexibility options during the COVID-19 pandemic.

To address this research question, we present data visualization and descriptive statistics on parameters for the change in the electricity system during the COVID-19 pandemic. We first concentrate on Europe and describe the different exogenous shocks that occurred during the COVID-19 pandemic, including the change in electricity demand (cf. Section 2). Thereafter, we focus on Germany and analyze the corresponding endogenous effects on the electricity system in more detail. During the COVID-19 pandemic, the German electricity system was in the midst of a transformation that includes plans for the phasing out of nuclear energy by 2022 and coal by 2038. [4] stress that now is the time to reconfigure electricity systems and consider flexibility as a central component. Therefore, we discuss how different flexibility options contributed to a secure electricity system (cf. Section 3). Finally, we conclude our paper in Section 4.

2. How COVID-19 affected electricity systems

In this section, we use data visualization and descriptive statistics to provide initial insights to reveal how the parameters of electricity systems have evolved during the COVID-19 pandemic. For this purpose, we use publicly available data to analyze and visualize relevant indicators of electricity systems and markets. There are very few data points missing in the following data sets: electricity generation in Germany in 2018; electricity consumption in Germany in 2018 and 2019; electricity consumption in Spain in 2017, 2018, and 2020; electricity consumption in Sweden in 2019; grid frequency in central Europe of the years 2016, 2017, 2018, 2019, and 2020; automated Frequency Restoration Reserve (aFRR) in Germany in the year 2017. The remaining data sets are complete. We use a linear interpolation to eliminate these missing data points. The data visualization and descriptive statistics allow us to gain an understanding of the European – and, specifically, German – electricity system during the COVID-19 pandemic and, thus, provides a starting point for further examinations. In order to contextualize these insights and discuss the role of various flexibility options, we structure this section as follows: We begin our analyses with a brief description of the exogenous shocks and the effects of the COVID-19 pandemic on the European electricity consumption (cf. Section 2.1). In the second section (cf. Section 2.2), we focus on Germany and analyze changes in the nation's electricity generation (cf. Section 2.2.1). Due to shifts in demand and changes in the merit order, there may also be an impact on wholesale electricity prices (cf. Section 2.2.2). Changes in electricity consumption and generation may also lead to altered electricity imports and exports (cf. Section 2.2.3). Furthermore, based on data concerning grid frequency, we present the development of the grid stability itself and mechanisms for ensuring grid stability (cf. Section 2.2.4).

For our analysis of the exogenous shock to the energy system – in particular, the electricity system – we use data from different European countries. Some of these countries were imposing a range of different restrictions (e. g., Italy) while others fought the COVID-19 pandemic by imposing comparatively few restrictions (e. g., Sweden). In this paper, we focus on a period of restrictions during the first wave of the COVID-19 pandemic, which allows us to examine in detail the effects of the pandemic; namely, the effect the increased share of RES had on the electricity system. We define the beginning of the period under examination as the date of external border closures in the European Union for non-essential travel that is the 17th of March, 2020 [29]. At the end of May, Germany successively relaxed restrictions. We, therefore, focus on the period from 17th March (77th day of the year 2020) to the 31st May (152nd day of the year 2020), which is likely to be the period in which the short-term effects of the COVID-19 pandemic are most noticeable in the electricity system.

2.1. Exogenous shocks on electricity systems

Fig. 1 demonstrates that restrictions during the COVID-19 pandemic had a noticeable impact on electricity consumption. Two vertical lines in each plot represent the beginning and end of our period of interest. Electricity consumption is aggregated over 24 hours and covers the years 2017 to 2020, with the previous years allowing for a comparison with recent consumption levels. We consider France, Germany, Italy, and Spain as they are the largest economies in the European Union based on the gross domestic product [30]. In addition, the corresponding electricity systems exhibit different characteristics regarding electricity generation and demand. We also take Sweden into account, as the Swedish government has chosen a different way to fight the COVID-19 pandemic. The approach chosen by the Swedish government based on calling upon the citizens' own responsibility instead of implementing strict measures like a country-wide lockdown [31]. This allows us to approach the research question with a broader view. Finally, we specifically focus on Germany.

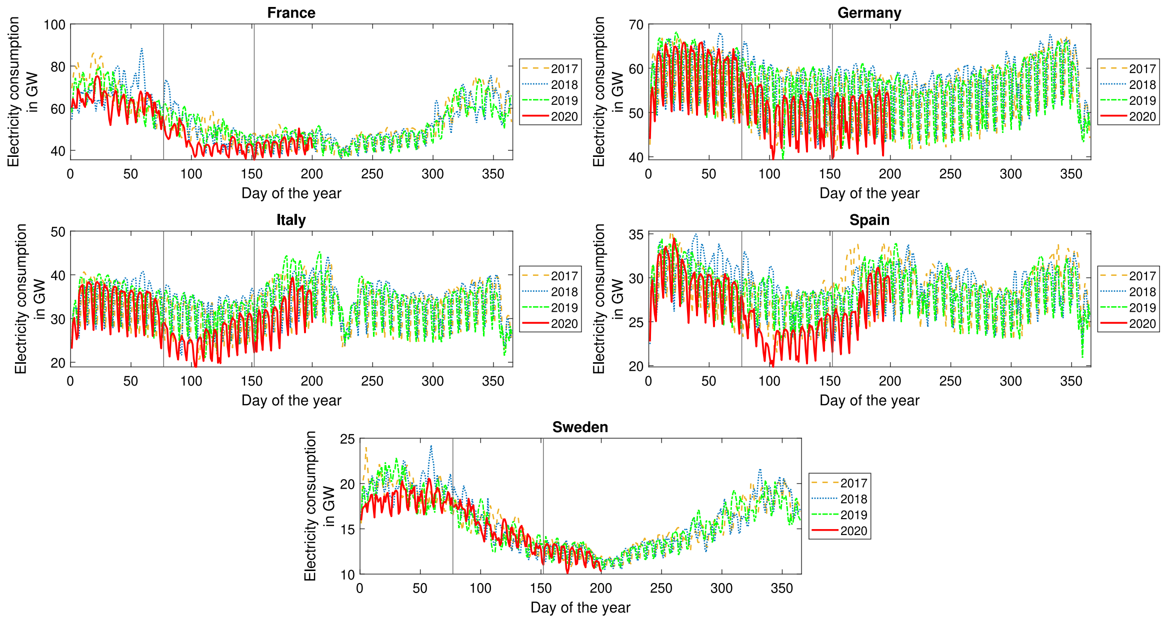


Fig. 1. Electricity Consumption in France, Germany, Italy, Spain, and Sweden.
Source: Own illustration, data from [32].

In addition to the regular seasonal fluctuations in electricity consumption – e. g., due to the use of electric heating – Fig. 1 illustrates that with respect to previous years, absolute electricity consumption in the five European countries declined with the introduction of COVID-19 restrictions in comparison. Note that we do not correct the underlying data on electricity consumption for other influencing factors like the outside temperature. The observed effects may also be influenced by, e. g., a mild winter. This may explain the lower consumption level of Sweden at the beginning of 2020 compared to the previous years. Particularly this applies with regard to the fact that in France, for instance, a higher amount of electricity is used for heating compared to other countries.

The exception in terms of the decline in electricity consumption was Sweden, where electricity consumption remained largely consistent with that of previous years. This may be due to the fact that Swedish politicians decided not to impose major restrictions and, generally, public life was not shut down as it was in other countries.

In Fig. 2, we consider the changes in weekday electricity consumption compared to weekends/bank holidays in Germany and Spain. We examine these two countries as two European examples with different restrictions and effects of the COVID-19 pandemic. With regard to the temporal electricity consumption patterns, there are different effects in Spain and Germany. In France, Italy, and Sweden we do not observe any changes in the temporal electricity consumption. To highlight these differences, we exemplarily discuss Spain and Germany in the following. Fig. 2 depicts the German and Spanish daily electricity consumption for 2017 until 2020, separated into weekdays and weekends/bank holidays. Again, two vertical lines demarcate our period of interest.

The figure illustrates that, at the beginning of our period of interest, electricity consumption fell in both countries, particularly on weekdays. According to Fig. 2, electricity consumption is generally lower on weekends and bank holidays than it is on weekdays. Moreover, the figure indicates that, in comparison to the same period in previous years, electricity consumption decreased in both countries on weekends and holidays (average per day in Germany: 1.12 TWh (2017), 1.15 TWh (2018), 1.12 TWh (2019), 1.05 TWh (2020); average per day in Spain: 586 GWh (2017), 608 GWh (2018), 588 GWh (2019), 521 GWh (2020)) but not by the same magnitude as on weekdays (average per day in Germany: 1.40 TWh (2017), 1.43 TWh (2018), 1.42 TWh (2019), 1.29 TWh (2020); average per day in Spain: 679 GWh (2017), 697 GWh (2018), 682 GWh (2019), 587 GWh (2020). With the help of the Student's two sample t-Test, we can statistically compare the average values of power consumption on weekdays in Germany during our period of interest in the respective years. Table 1 lists the values of the F- and t-Test for the combination of years considered by us. The values indicate that the years 2017 and 2018 significantly differ on average at a significance level of 0.05. Also, the values for the year 2020 imply that the electricity consumption on weekdays significantly differs on average between each year considered by us, i. e., 2017, 2018, and 2019, at a significance level of 0.001.

Table 1
F- and t-values for electricity consumption on weekdays in Germany.

		2017	2018	2019	2020
2017	F-value	1			
	t-value	0			
2018	F-value	0.4642^{**}	1		
	t-value	-2.2128^{*}	0		
2019	F-value	0.8803	1.8964^{*}	1	
	t-value	−1.3619	1.0858	0	
2020	F-value	0.5781	1.2454	0.6567	1
	t-value	11.9052^{***}	11.9345^{***}	12.8661^{***}	0

*Significance: $p < 0.05$, $^{**}p < 0.01$ $^{***}p < 0.001$.

Fig. 3 illustrates how the COVID-19 pandemic affected consumption in Germany and Spain. The figure depicts the average, maximum, and minimum load profile for weekdays in both countries during our period of interest.

Lower consumption is clearly visible for the average load profile as well as for the maximum and minimum in both Germany and Spain. For Germany as a whole, Fig. 3 depicts that there are basically no recognizable changes in electricity consumption patterns. The average power consumption indicates only that the maximum consumption at lunchtime occurred a quarter of an hour later than in 2017 and 2018. In the years 2017 and 2018, the maximum in the average load profile is at the 43th measuring point, respectively. In 2019 and 2020, the maximum is at the 44th measuring point (cf. data points in the upper left plot in Fig. 3), i. e., a quarter of an hour later.

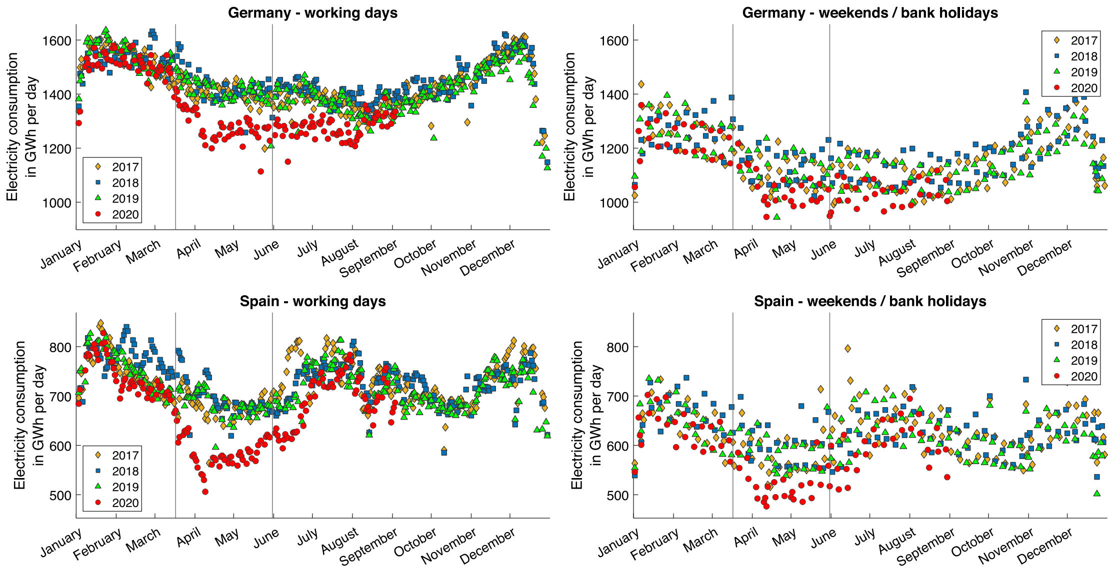


Fig. 2. Electricity Consumption in Germany and Spain on weekdays and weekends/bank holidays.
Source: Own illustration, data from [32].

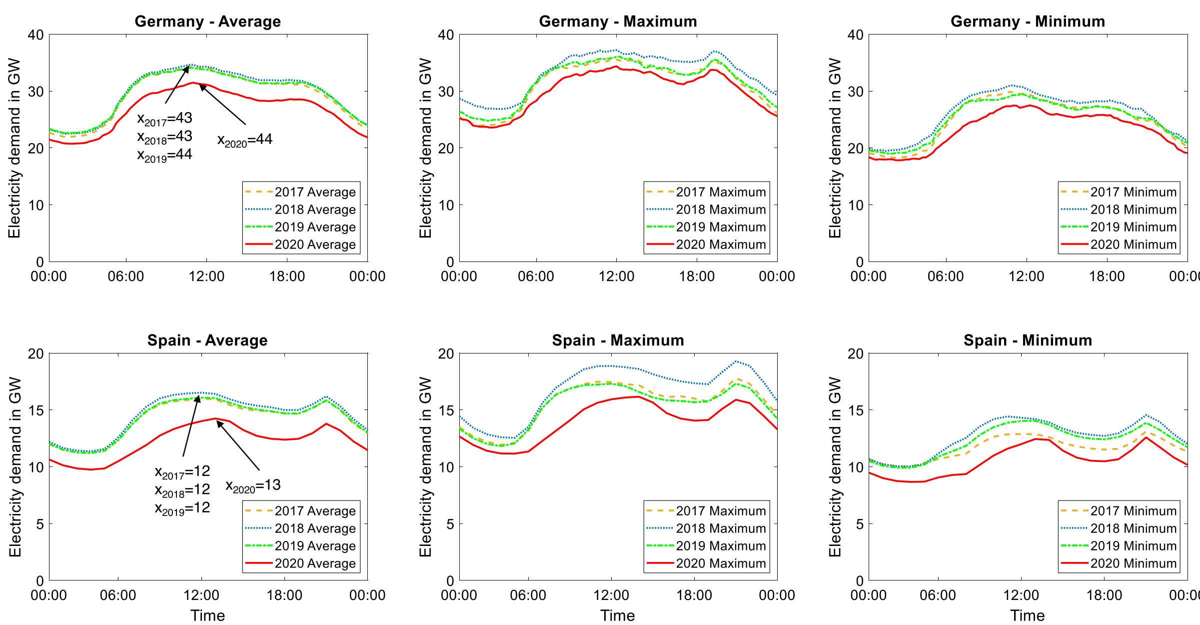


Fig. 3. Load profile in Germany (resolution 15 min) and Spain (resolution 60 min) on weekdays, each for the interval from 17th March until 31st May.
Source: Own illustration, data from [32].

Examining the temporal load profile for Spain, however, Fig. 3 indicates some changes in temporal patterns of electricity consumption. While the peak in the evening consumption occurs at about the same time, the peak at midday in 2020 appears later than in previous years (cf. data points in the lower left plot in Fig. 3).

2.2. Endogenous effects on electricity systems

Given the exogenous shocks, including the effects on electricity consumption described above, in this section, we present the visualizations of different parameters of the electricity system and relevant markets. From now on, we will focus our observations on Germany.

2.2.1. Electricity generation

The decline in absolute electricity consumption (cf. Section 2.1) had a direct impact on electricity generation, particularly on the proportion of individual electricity generation sources. Moreover, the oil and gas price shocks affected the electricity supply-side, as the marginal costs of conventional power plants influenced the merit order.

Fig. 4 illustrates the percentages of electricity generation per generation source from 2015 until 2020, each for our period of interest. The order of the generation technologies reflects their share in the year 2020. In 2011, Germany decided to shut down all nuclear power plants before 2022. Therefore, overall, the share of nuclear power plants has steadily decreased since 2015, independent of the COVID-19

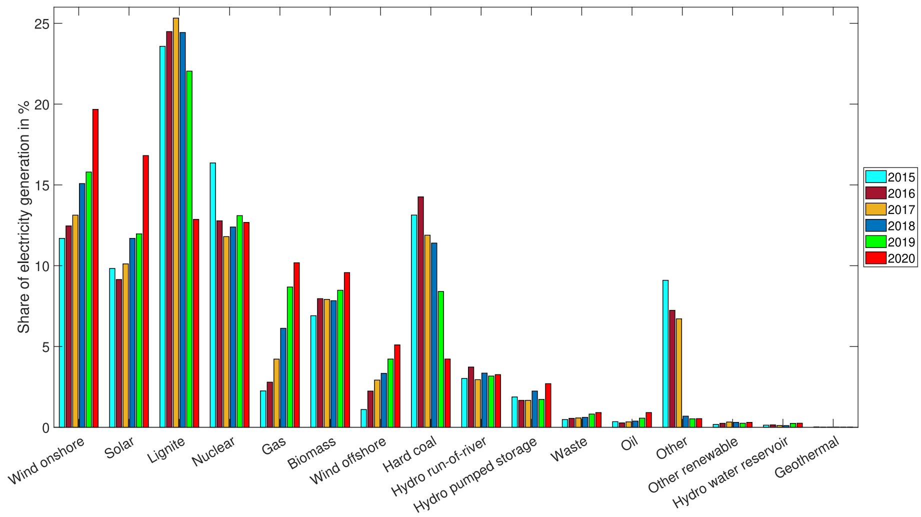


Fig. 4. Percentage of the different electricity generation technologies in total electricity generation in Germany from 2015 until 2020, each for the interval from 17th March until 31st May.
Source: Own illustration, data from [32,33].

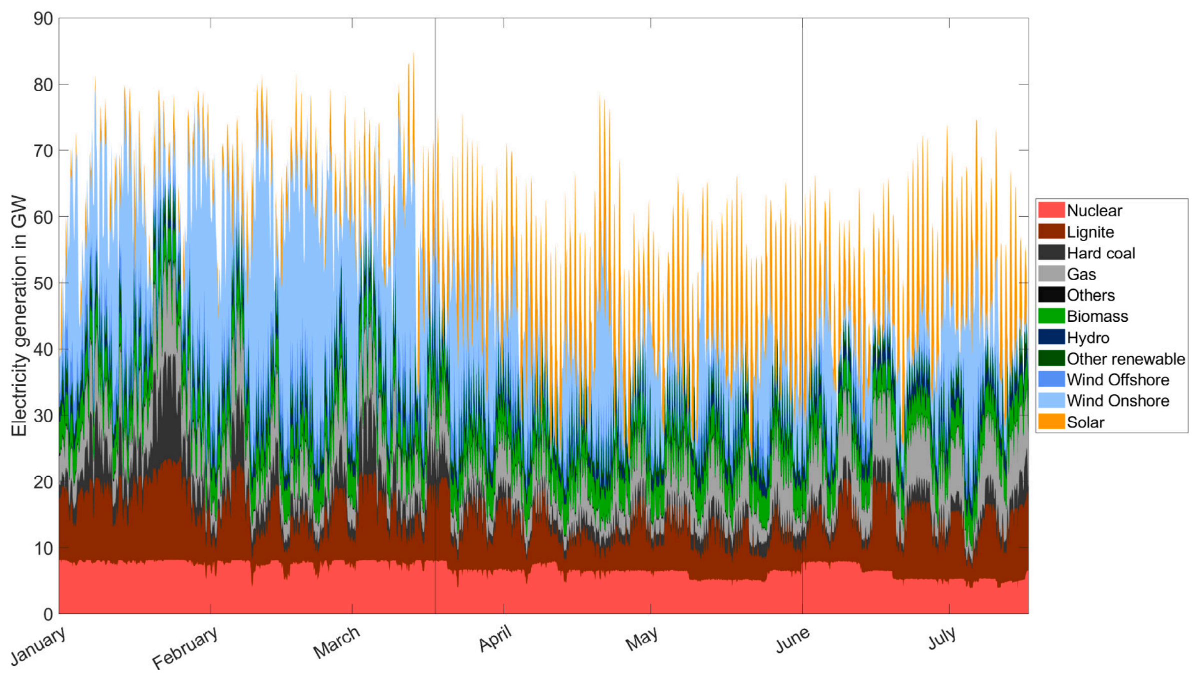


Fig. 5. Electricity generation in Germany in 2020 (resolution 60 min).
Source: Own illustration, data from [33].

pandemic. Although in January 2020 the German government decided to phase out coal-fired power generation by 2038, measures to reduce generation were not implemented before or during the period of interest [34,35]. Still, we can see that the share of electricity produced by hard coal-fired power plants has fallen considerably compared to previous years.

To allow for a closer look at the year 2020, Fig. 5 depicts the actual aggregated net generation output per hour. Again, two vertical lines again demarcate our period of interest. In addition to the aggregated information from Fig. 4, Fig. 5 allows a temporally finer granular evaluation of the individual generation technologies. Despite their volatile feed-in characteristics (cf. Fig. 5), onshore wind and solar generated the largest amount of electricity during the pandemic (cf. Fig. 4). As in Fig. 4, we can see that coal-fired power plants, in particular, reduced their electricity generation from the end of March, thus limiting their share of the total output.

2.2.2. Electricity prices

In Fig. 6, we visualize data from the day-ahead market in Germany during the COVID-19 pandemic.[1] Fig. 6 depicts the hourly day-ahead prices from 2017 to 2020 as boxplots for three periods: the interval before the COVID-19 pandemic, the COVID-19 pandemic, and the interval after the first wave of the COVID-19 pandemic. During

[1] Until September 2018, Austria, Germany, and Luxembourg formed a joint market area. In October 2018, Austria left the joint market area and now forms its own market area alongside Germany/Luxembourg.

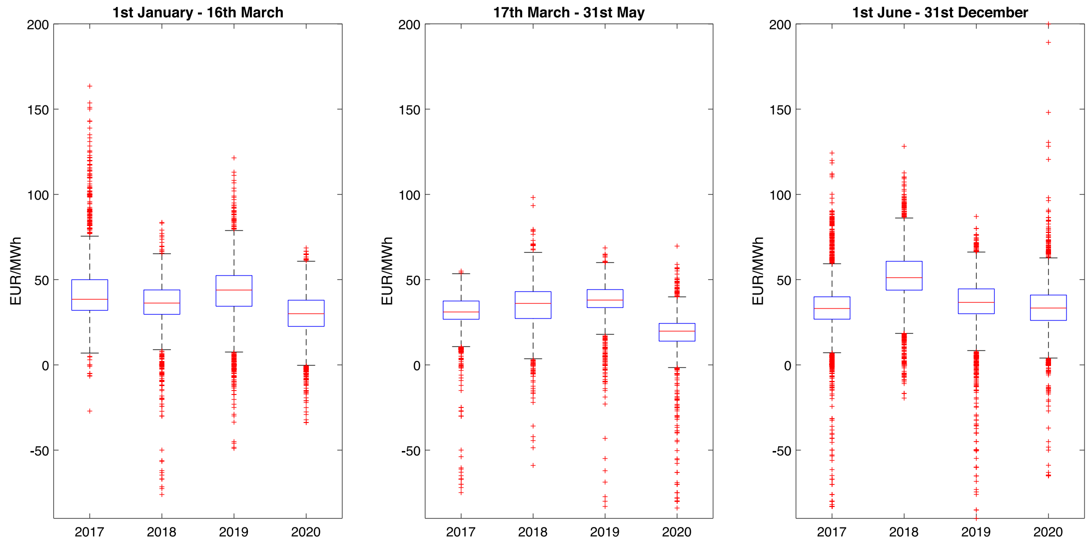


Fig. 6. Electricity prices on the day-ahead market in Germany. For 2020, electricity prices up to the 30th September are considered. *Source:* Own illustration, data from [36].

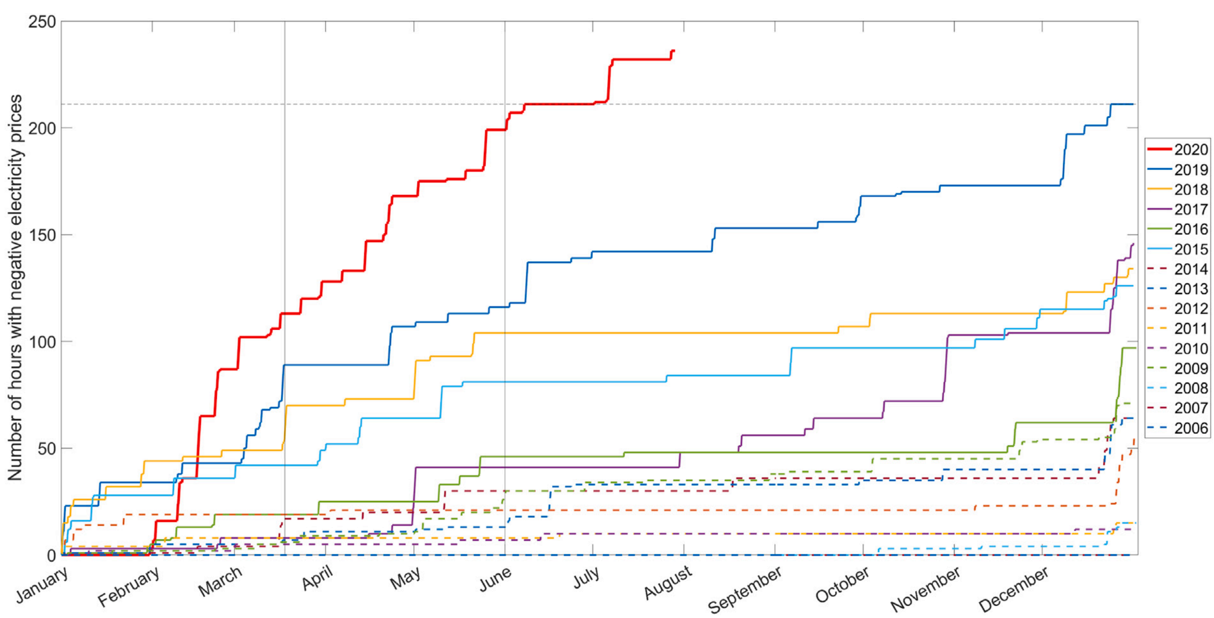


Fig. 7. Cumulated number of hours with negative electricity prices on the day-ahead market. *Source:* Own illustration, data from [36].

the COVID-19 pandemic, the average price on the day-ahead market was 17.60 EUR/MWh, while the average price in the same period was 29.95 EUR/MWh in 2017, 34.69 EUR/MWh in 2018, and 37.37 EUR/MWh in 2019 [36]. In addition, for the period of the COVID-19 pandemic Fig. 6 reveals, that in 2020 the 75th percentile is lower (24.52 EUR/MWh) than the 25th percentile of 2017 (26.70 EUR/MWh), 2018 (27.08 EUR/MWh), and 2019 (33.85 EUR/MWh) which underlines the lower price level in 2020.

Table 2 summarizes the values of the F- and t-test for the combination of years considered by us for electricity prices in Germany during the COVID-19 pandemic. The table reveals that electricity prices significantly differ on average at a significance level of 0.001 for all year combinations. However, the t-values indicate that for 2020 the differences between each year are the greatest.

Fig. 6 already indicates recurrent negative prices in the electricity sector during the COVID-19 pandemic. Fig. 7 now illustrates the number of hours with negative prices on the day-ahead market in Germany for the years 2006 to 2020 [36]. In 2019, a new record of 211 hours with negative prices was set. In 2020, this level had already been reached by 6th June and has, since, continued to increase.

2.2.3. Electricity imports and exports

Fig. 8 illustrates total electricity imports and exports, i. e., the total scheduled commercial exchanges from explicit and implicit allocations between Germany and its neighbor countries, again for the three corresponding time periods [37]. In particular, Fig. 8 comprises the hourly aggregated exchange of Germany with the following countries: Austria, Switzerland, Czech Republic, Denmark, France, Luxembourg, Netherlands, Poland, and Sweden. The upper boxplots represent imports, the

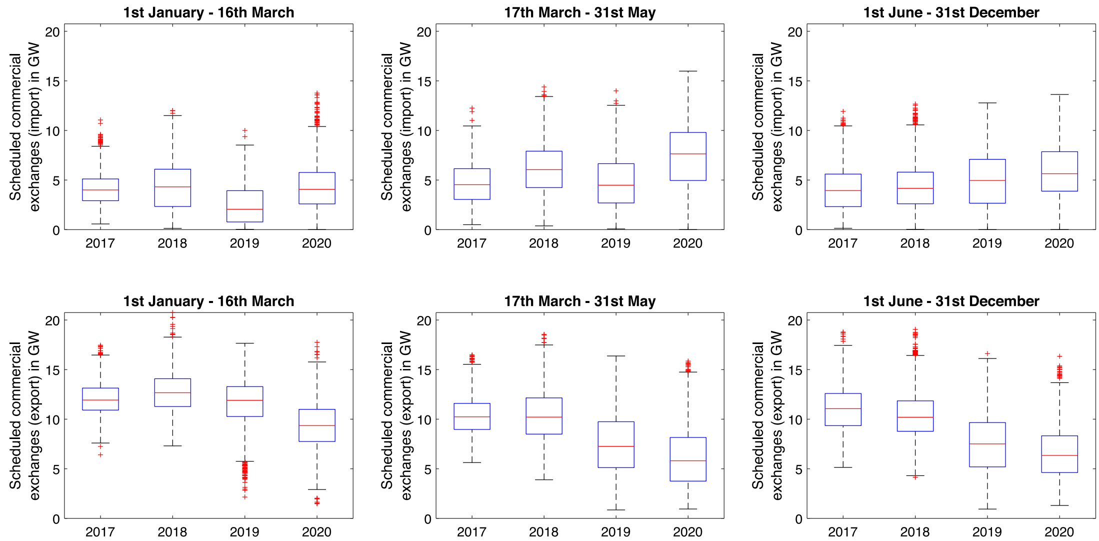


Fig. 8. Total scheduled commercial exchanges (imports and exports) of Germany with neighboring countries. For 2020, imports and exports up to the 7th October are considered. *Source:* Own illustration, data from [37].

Table 2
F- and t-values for electricity prices in Germany.

		2017	2018	2019	2020
2017	F-value	1			
	t-value	0			
2018	F-value	0.8477***	1		
	t-value	−10.5837***	0		
2019	F-value	1.0908	1.2868***	1	
	t-value	−17.6584***	−6.0929***	0	
2020	F-value	0.7775***	0.9171	0.7127***	1
	t-value	26.8845***	35.8371***	43.8592***	0

*Significance: $p < 0.05$, $^{**}p < 0.01$ $^{***}p < 0.001$.

lower boxplots represent exports. We consider the absolute values for electricity imports and exports, i. e., we did not correct the data for outside temperatures, precipitations, or snow melting periods which may have an impact on a country's electricity generation mix, prices, imports, and exports.

For the interval of the COVID-19 pandemic, the boxplots (center column) reveal a higher amount of imports, including a new maximum and a greater scattering (cf. the height of the box for exports in 2020), and simultaneously a smaller amount of electricity exports for 2020 compared to previous years.

Figs. 9 and 10 depict matrices of plots to demonstrate correlations among day-ahead electricity prices and both, export and import exchanges. Each matrix comprises a histogram for electricity prices (top left) and imports/exports (right bottom). The two scatter plots visualize the imports/exports depending on the electricity price (left bottom) and the electricity price depending on the imports/exports (top right). In addition, the scatter plots include a regression line and the corresponding correlation coefficient. The correlation coefficient is a statistical measure and reflects the degree of linear connection between two measured variables. We consider our period of interest for the years 2017, 2018, 2019, and 2020.

In the scatter plot for electricity prices and exports, we can observe a negative correlation, i. e., increasing exports correspond to decreasing electricity prices. In the scatter plot for electricity prices and imports, we can observe a positive correlation, i. e., increasing imports correspond to increasing electricity prices. For both exports and imports, the correlation values for 2020 exhibit the lowest (−0.62), respectively highest value (0.63) for the period from 2017 until 2020 (cf. Fig. 9 (d) and Fig. 10 (d)), i. e. the negative/positive linear correlation between exports/imports and electricity prices was highest in absolute terms compared to the previous years.

2.2.4. Grid stability

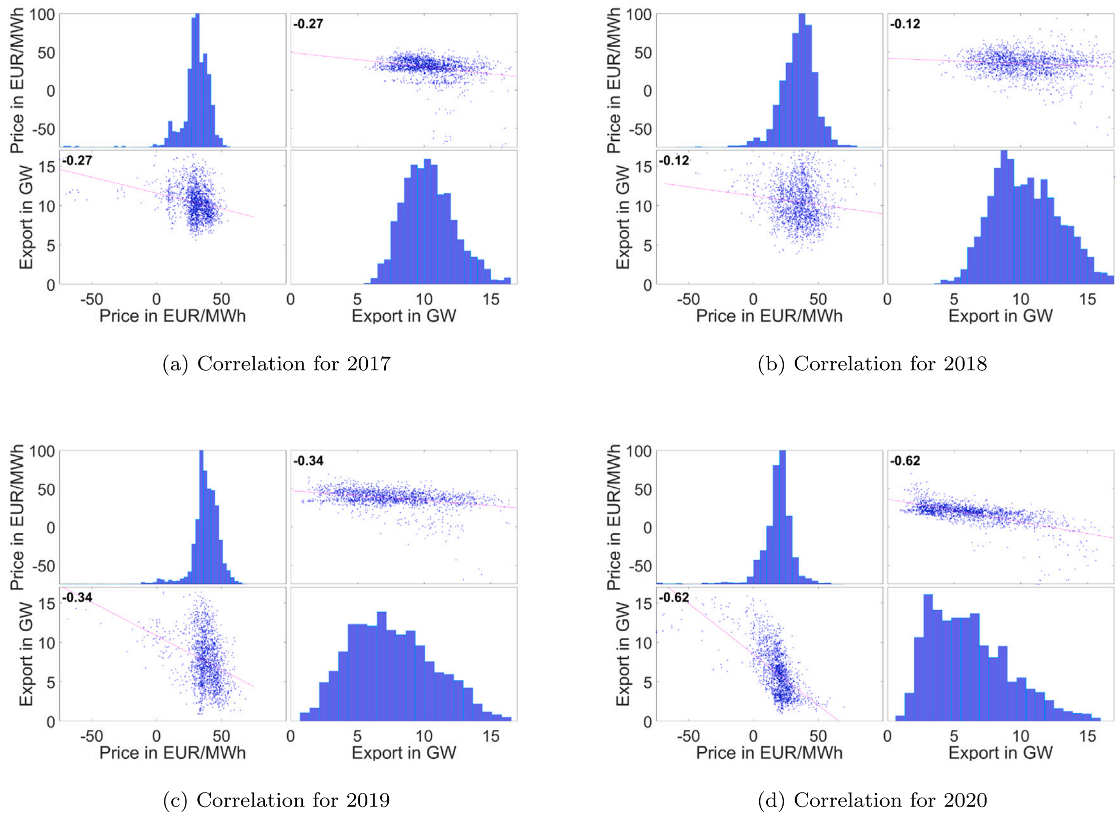
Grid frequency. The grid frequency serves as an indicator of the balance of electricity demand and supply. Fig. 11 contains data on the grid frequency between January 2015 and July 2020, with a resolution of 10 s in the form of a heatmap. Dark colors indicate a low grid frequency and light colors indicate a high. Again, two vertical lines highlight our period of interest (and not a low grid frequency). In contrast to, e. g., the voltage, the grid frequency is a global variable in electricity grids, i. e., the grid frequency in Germany relates to the coupled European electricity grid. The grid frequency, thus, allows us to expand our analysis to encompass the European integrated grid.

Concerning the grid frequency, negative deviations from the target value of 50.0 Hz represent a particular challenge. A frequency lower than 50.0 Hz means that more electricity is withdrawn than injected. The value of 49.8 Hz is critical in that, at frequencies below this value, power failures occur.

Fig. 11 depicts several patterns. Regarding changes in hours, the figure exhibits regular deviations. In the evening hours, the heatmap indicates a kind of a curve.

In spring 2018, the chart shows a period with higher grid frequency. This was a result of a power plant in Kosovo/Serbia temporarily producing too little electricity, leading to a deficit in the electricity budget [38]. As a result, it was necessary to generate more electricity, which resulted in a higher grid frequency, visible as a slightly brighter stripe in Fig. 11 [39]. However, note that Fig. 11 does not indicate that any comparable deviations from the historical development occurred during the COVID-19 pandemic.

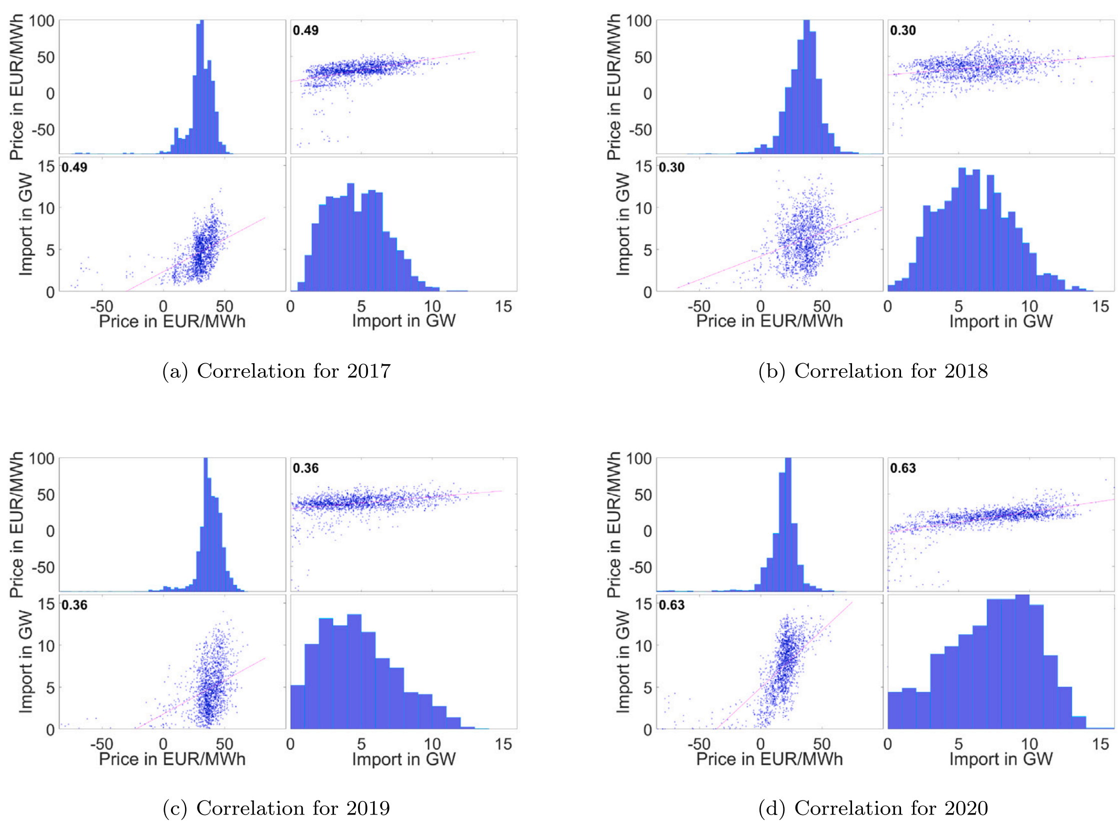
In Fig. 12, we can see the daily minimum and maximum grid frequency with a resolution of 10 seconds [40]. The filled areas represent the range of daily maxima and minima for the years 2015 to 2019. Like Fig. 11, Fig. 12 indicates that the grid frequency during the COVID-19 pandemic of 2020 has remained within the range of recent years.



(a) Correlation for 2017 (b) Correlation for 2018

(c) Correlation for 2019 (d) Correlation for 2020

Fig. 9. Correlation among electricity prices and total electricity exports of Germany with neighboring countries. *Source:* Own illustration, data from [36,37].



(a) Correlation for 2017 (b) Correlation for 2018

(c) Correlation for 2019 (d) Correlation for 2020

Fig. 10. Correlation among electricity prices and total electricity imports of Germany with neighboring countries. *Source:* Own illustration, data from [36,37].

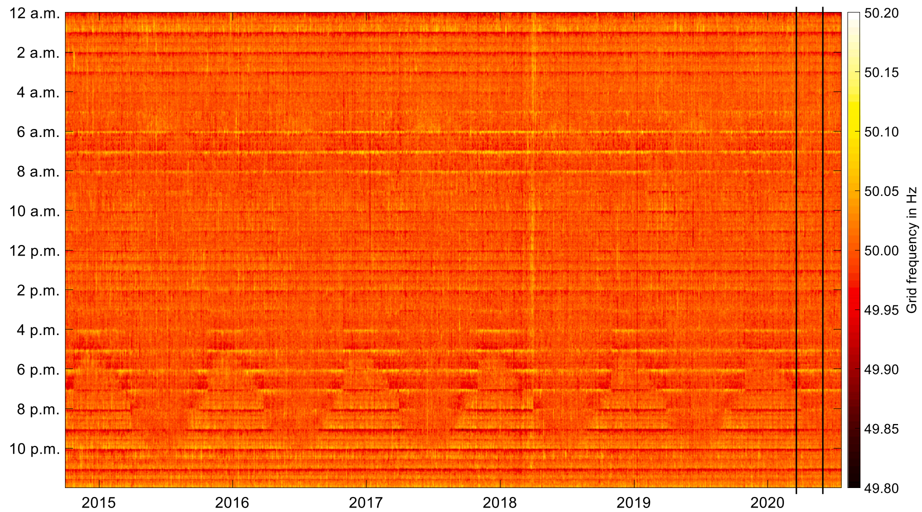


Fig. 11. Grid frequency (resolution 10 s) illustrated as a heat map.
Source: Own illustration, data from [40].

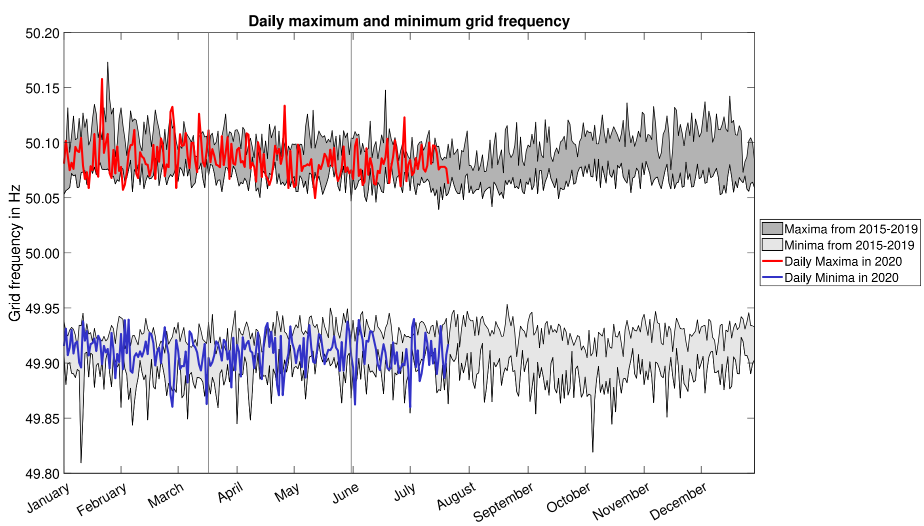


Fig. 12. Daily minimum and maximum grid frequency.
Source: Own illustration, data from [40].

Redispatch and balancing power. Safety mechanisms, such as redispatch and balancing power, keep the grid stable. Such mechanisms are particularly important when a large proportion of electricity is produced by RES.

To consider grid bottlenecks, Fig. 13 depicts the amount of positive and negative redispatch in Germany, which solves grid congestions. The data indicate that there were more upward outliers, especially in terms of the amount of positive redispatch during our period of interest, as compared to previous years [41].

Fig. 14 illustrates the positive and negative demands of aFRR on weekdays and weekends/bank holidays in Germany. Since the primary control power (Frequency Containment Reserve (FCR)) is directly driven by the grid frequency, it is critically important to quantify the balancing work. Therefore, we investigate the aFRR. Concerning positive aFRR on weekdays, the data points in Fig. 14 indicate that there was a slightly lower need for balancing energy in 2020 during our period of interest.

In addition to the required balancing work (cf. Fig. 14), we also analyzed the German balancing power market, i. e., the prices for FCR and aFRR [43]. The data for the FCR market indicate that, since January 2020 with the exception of 1st May 2020, there were no particular anomalies in the settlement price [43]. For aFRR, only the average energy price exhibits a slightly higher variance over the time segments of aFRR.

3. The role of different flexibility options during the COVID-19 pandemic

Based on Section 2, we can observe changes in the indicators of the electricity system and markets during the COVID-19 pandemic. These changes primarily occurred in electricity consumption, generation, day-ahead prices, and imports/exports. In contrast, the investigation of the grid frequency, redispatch, balancing power, and balancing power market did not reveal any noticeable effects of the COVID-19 pandemic.

Against this background, we now consider the role of different flexibility options and discuss whether a “flexibility gap” has arisen during the COVID-19 pandemic. Thereby, we rely on the flexibility options mentioned in the introduction: demand-side flexibility, sector coupling, supply-side flexibility, storages, and grid extension [17,22]. We, discuss the contributions that different flexibility options made to the German electricity system during the COVID-19 pandemic.

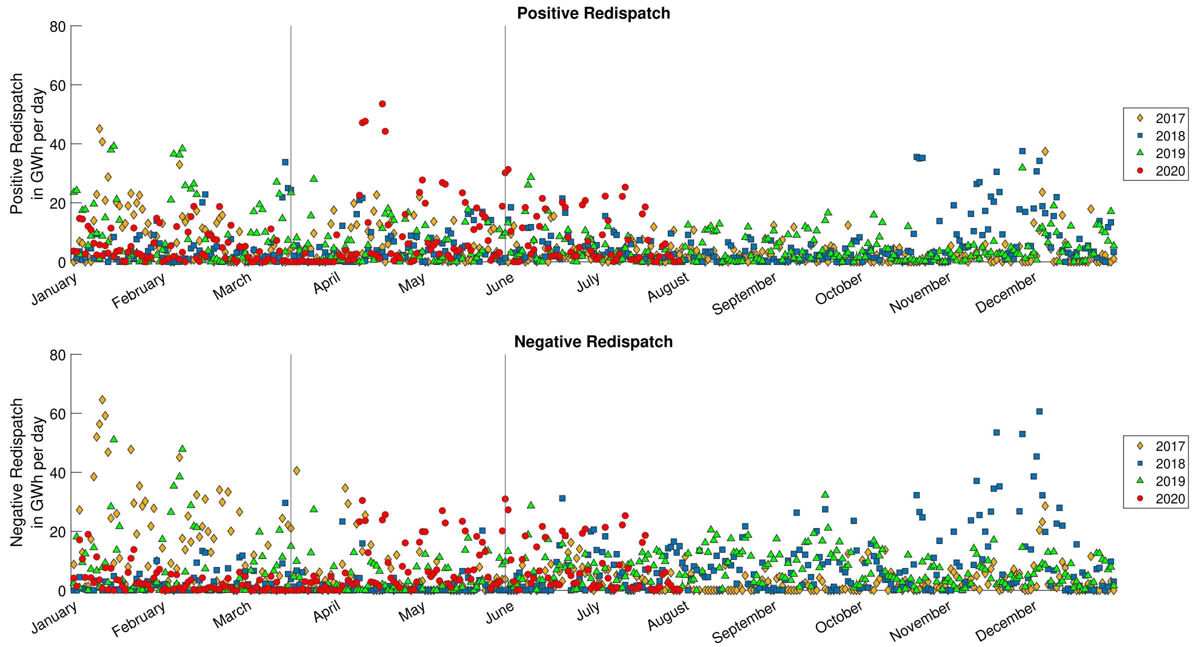


Fig. 13. Daily amount of positive and negative redispatch in Germany.
Source: Own illustration, data from [41].

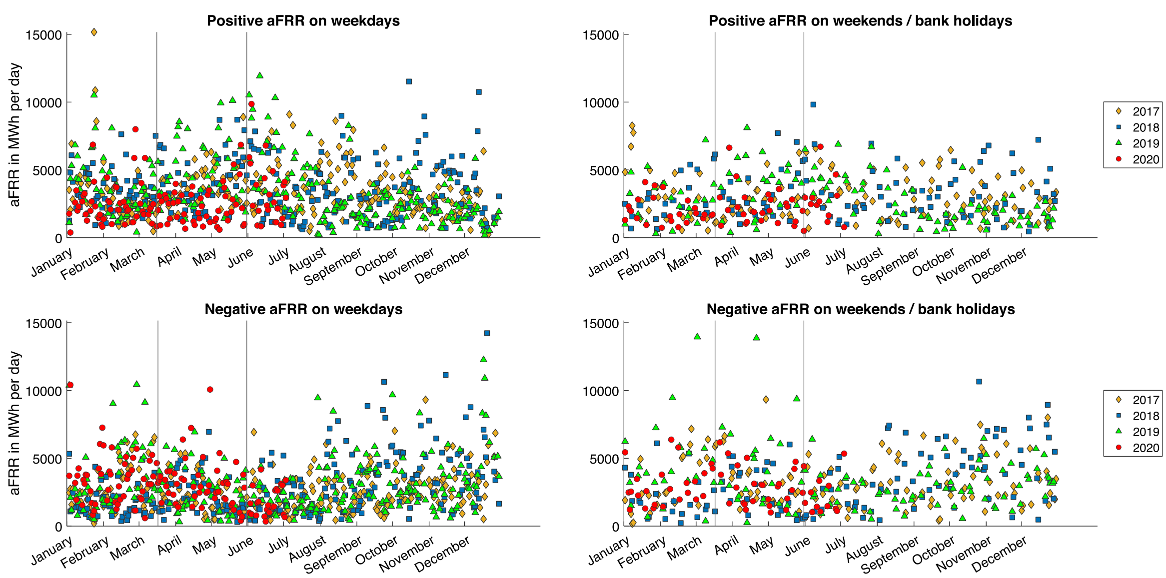


Fig. 14. Daily amount of positive and negative demands on aFRR.
Source: Own illustration, data from [42].

Demand-side flexibility. Demand-side flexibility is the possibility of adapting electricity consumption in response to a specific event or signal [44]. Depending on the industry, production may have been no longer close to, or at, full capacity. However, there have also been companies that had to increase their production, e.g., the pharmaceutical industry or manufacturers of medical devices. Both cases may have increased or decreased the flexibility potential of companies in the industrial sector. However, the considerable decline in electricity consumption during the period in question (cf. Fig. 1, Fig. 2, and Table 1) is most likely a consequence of the restrictions caused by the COVID-19 pandemic as an exogenous shock and not a result of increased demand-side flexibility. In terms of the load profile in Germany (cf. Fig. 3), our data describe little noticeable deviations from the data of the same period in previous years, i. e., there is hardly any visible reaction on the demand-side to the shocks in the electricity system, apart from the general load decrease. The slight change in the temporal load profile – the maximum of the midday peak occurs a quarter of an hour later – may be due to, among other things, changed conditions such as more remote work. In addition, the high number of negative electricity prices (cf. Figs. 6 and 7) may also indicate that the demand-side reacted only in a limited way to changes in the electricity system. This may be due to the fact that the demand side is currently only partially able to adapt their electricity consumption, or to the fact that companies had to focus on topics more urgent than demand-side flexibility during the pandemic.

Sector coupling. Sector coupling refers to both the coupling of the electricity sector with the heat or mobility sector and the consideration of corresponding transmission capacities [45,46]. From the perspective of the electricity sector, sector coupling would impact electricity consumption, particularly when electricity prices are low.

Similar to our discussion on demand-side flexibility, we conclude that the use of sector coupling as a flexibility option did not increase during the COVID-19 pandemic by an amount visible in our analysis.

Supply-side flexibility. Supply-side flexibility entails a response by electricity generation units to ensure the electricity system's balance [17]. During the COVID-19 pandemic, a decline in electricity consumption combined with favorable weather conditions resulted in RES generating a high proportion of electricity (cf. Figs. 4 and 5). Yet, as discussed above, RES provide little flexibility and conventional power plants generated less or no electricity at all, and the increasing proportion of RES led to a decrease in supply-side flexibility [17,22].

Furthermore, declining gas prices led to lower marginal costs for gas power plants. Thus, some gas turbines that usually provide supply-side flexibility by generating electricity in times of low shares of RES generally increased their generation during the COVID-19 pandemic. As a consequence of the merit order effect, the proportion of electricity generated by hard coal power plants declined (cf. Fig. 4). These circumstances also led to a reduction in supply-side flexibility as some gas turbines turned from a flexibility option into a general electricity provider and comparatively inflexible coal power plants had to take over the role of gas power plants as flexibility providers.

Storage. There are different types of storage that can provide flexibility to electricity systems. These types of storage, e. g., hydro pumped or battery storage, generally differ from others in their power and storage capacity [17]. As Fig. 4 depicts, the share of hydro-pumped storage increased slightly during the COVID-19 pandemic. Furthermore, during the COVID-19 pandemic prices for balancing power remained stable (cf. Section 2.2.4). This level of stability might result from the fact that, in Germany, battery storage already contributes a large part of the FCR [47]. As a result, the supply of balancing power remained sufficient even in the absence of conventional power plants. These observations indicate that flexibility provided by storage still contributed to grid stabilization under (near) constant prices for balancing power.

Grid extension. The grid can also provide geographic flexibility as it bridges the gap between local electricity consumption and decentralized electricity generation. As a result of the COVID-19 pandemic, electricity demand in Germany decreased and differed on average significantly compared to previous years (cf. Table 1). Thus, the grid had to transport less electricity. This situation led to an improved relationship between grid capacity and electricity consumption/generation. We can interpret this as a relative extension of the grid and therefore as an expansion of this flexibility option. However, the amount of redispatched energy increased in comparison to the same period in the year before (cf. Section 2.2.4). This may be due to the higher share of volatile RES in the energy system. Regarding the electricity grid, it is also necessary to consider couplings with other countries. For instance, our analyses revealed that Germany increased the electricity imports from neighboring countries during the COVID-19 pandemic.

Discussion of the role of flexibility options. In the following, based on the analyses and discussion above we summarize, how the electricity system responded to the altered circumstances and in this way, derive our key findings. Despite the unexpected rapid changes in circumstances, the stability of the European electricity system – with grid frequency as one key indicator – was similar to that of previous years (cf. Figs. 11 and 12). Also, efforts regarding the security of supply are comparable to one of the previous years. Hence, our analysis indicate that during the COVID-19 pandemic there was no threat of a blackout, although the German electricity system faced a high share of RES.

With regard to the market, the decline in consumption and a high proportion of RES affected the merit order and the day-ahead market. For instance, until 2019 lignite has been the electricity generation technology with the largest share during our period of interest. In 2020, onshore wind and solar power plants were the two leading electricity generation technologies during our period of interest. In addition, the price level on the day-ahead market was lower than the one in previous years. Also, in 2020 electricity prices compared to previous years on average differed the most (cf. Table 2). Among others, limited short-term flexibility of conventional power plants led to an increased number of hours with negative electricity prices during the first wave of the COVID-19 pandemic and, therefore, indicates that the current electricity system lacks flexibility options or at least does not use them efficiently [48].

Regarding current electricity systems with an increased share of RES, our analyses reveal that the grid stability remained high. However, due to the decreased electricity consumption, in particular, a relatively higher grid capacity may have contributed to grid stability. In addition, Germany imported more electricity during the COVID-19 pandemic. This may also have contributed to grid stability.

4. Conclusion and outlook

The COVID-19 pandemic led to significant changes in many areas of our lives. In this paper, we focused on the effects of the first wave of the COVID-19 pandemic on the electricity sector, in particular in Germany. Thereby, to the best of our knowledge we are the first to present how the electricity system responded to altered circumstances and how various flexibility options contributed to a stable electricity system during the COVID-19 pandemic. Based on data detailing electricity consumption, generation, prices, imports/exports, grid frequency, redispatch, and balancing power, we used data visualization and descriptive statistics to analyze the performance of the electricity system during the COVID-19 pandemic. Also, we discussed the roles of various flexibility options during the COVID-19 pandemic.

Our contribution comprises an illustration of the behavior of the German electricity system together with corresponding electricity markets and a discussion of the role of different flexibility options during the crisis. The COVID-19 pandemic demonstrated that it is possible to integrate an increased share of Renewable Energy Sources into a changing electricity system at a continuously high level of security of supply. From a market perspective, the decreased electricity consumption and a higher share of Renewable Energy Rources led to a lower price level on the day-ahead market compared to previous years as well as an increased number of hours with negative electricity prices. These conditions had a short-term impact on the profitability of conventional power plants, which also may have led to negative effects on new investments on the generation side. With regard to new flexibility options, such as storage, there was a short-term increasing attractiveness for investments. However, the rapidly altered circumstances during the COVID-19 pandemic accompanied by the previously already existing uncertainty about energy policy may generally have led to an increasing uncertainty about corresponding revenue streams from investments in flexibility options. Also, during the COVID-19 pandemic there existed special circumstances like a relatively higher grid capacity that are unlikely to reoccur in the mid-term future. Our work emphasizes the value of flexibility options for the operation of electricity systems. In the low-carbon transformation of current electricity systems, it is necessary to integrate sufficient flexibility to ensure grid stability also in the future.

However, our work has some limitations. We focused our analyses on the effects in the German electricity system as a system with a high share of Renewable Energy Sources during the COVID-19 pandemic. Also, our analyses on grid frequency, redispatch, and balancing power, in particular, shed first light on the system's behavior in the transmission grid. These indicators represent the system's reaction on the distribution level only to a limited extent. Nevertheless, our work can serve as a starting point for further analyses to broaden the understanding of various flexibility options during the COVID-19 pandemic.

Such analyses could, for instance, isolate the effect of the COVID-19 pandemic by eliminating the influence of, e. g., weather conditions or altered electricity imports and exports, respectively. It is worthwhile to analyze the response of electricity systems in other countries as well as the interaction and interdependencies of different interconnected electricity systems such the ones in Europe in more detail. Thereby, prospective research could also deepen the analysis on the impact of altered imports and exports on electricity prices by investigating country-specific changes. Additionally, further questions about flexibility options during and after the COVID-19 pandemic – accounting for, e. g., future developments like a changing electricity demand – could be analyzed. Based on additional data for different sectors such as the industrial sector, transport, residential, and commercial and public services, it would, moreover, be worthwhile to extend the analyses of changes in electricity consumption patterns of Section 2.1. Such analyses could provide further insights into why changes in temporal electricity consumption have occurred in some countries and not in others during the COVID-19 pandemic. With regard to the distribution level, based on additional data, it would be worthwhile investigating the temporal discrepancy of electricity generation and consumption as well as further indicators of grid stability. Further research could analyze, for example, voltage maintenance in the electricity grid during the COVID-19 pandemic. Furthermore, it is necessary to examine the question of how the COVID-19 pandemic affected the pathway of the energy transition, in more general terms.

We not only need to find useful answers to such questions but also to make sure that the mid-term fight against the COVID-19 pandemic ensures progress in the long-term battle against climate change. In Germany, policymakers followed scientific advice in combating the spread of COVID-19 pandemic. Initial indications suggest that the public's trust in science has played a key role in the success of this strategy. It may well now be the case that policymakers and the general public place more trust in scientific advice, which may help researchers in their search for answers and support the rapid and effective implementation of our fight against climate change.

CRediT authorship contribution statement

Stephanie Halbrügge: Conceptualization, Investigation, Writing - original draft, Data analyses, Visualization. **Paul Schott:** Conceptualization, Investigation, Writing - original draft, Data analyses, Visualization. **Martin Weibelzahl:** Conceptualization, Investigation, Writing - original draft, Editing. **Hans Ulrich Buhl:** Conceptualization, Writing - editing, Supervision. **Gilbert Fridgen:** Conceptualization, Writing - editing, Supervision. **Michael Schöpf:** Conceptualization, Investigation, Writing - editing.

Acknowledgments

The authors gratefully acknowledge the financial support of the Kopernikus-Project "SynErgie" by the Federal Ministry of Education and Research of Germany (BMBF) and the project supervision by the project management organization Projektträger Jülich (PtJ).

Supported by PayPal and the Luxembourg National Research Fund FNR, Luxembourg (P17/IS/13342933/PayPal-FNR/Chair in DFS/ Gilbert Fridgen).

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