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How Germany achieved a record share of renewables during the COVID-19 pandemic while relying on the European interconnected power network

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ABSTRACT

In 2020, Germany reached a maximum share of 50.5% intermittent renewables in electricity generation. Such a high share results in an increasing need for flexibility measures such as international transmission flexibility, i.e., electricity imports and exports. In fact, during the COVID-19 pandemic, Germany changed from a former electricity net exporter to a net importer. This paper, therefore, analyzes what we can learn from the resulting development of German electricity imports as a flexibility measure from a market, environmental, and network perspective. We analyze data on electricity imports/exports, generation, prices, and interconnection capacities of 38 bidding zones, respectively 11 countries within the ENTSO-E. In particular, we formulate three hypotheses to partition our overarching research question. Our results reveal that from a market perspective, Germany's increased need for transmission flexibility did not generally result in increased prices for German electricity imports. Also, from an environmental perspective, Germany increasingly relied on electricity imports from countries that exhibited a lower share of renewables. Finally, during the COVID-19 pandemic some of Germany's interconnection capacities to its neighboring countries exhibited a higher utilization. In view of our results, German policymakers may reflect on decarbonization policies considering a holistic European perspective.

1. Introduction

In 2020, the share of intermittent Renewable Energy Sources (RES) in the German electricity generation rose to 50.5% [1]. This implies an increase of 4.5% points compared to 2019. During the COVID-19 pandemic, countermeasures in terms of, e.g., restricted mobility and social distancing caused, for instance, a decrease in transport activities. These countermeasures had led to lower energy consumption, which in turn contributed to an increasing share of RES. Even though, changes appeared throughout the whole energy system, in this paper, we focus on changes within the electricity sector. Literature already investigates a reduction in electricity consumption with regard to corresponding changes in electricity systems worldwide during the COVID-19 pandemic [2]. In Germany, the biggest economy in Europe, the COVID-19 pandemic also led to a decrease in economic activities that resulted in a decline in electricity consumption [3–5]. A lower electricity consumption, combined with favorable weather conditions, contributed to an increasing share of RES during the COVID-19 pandemic. Moreover, the decline in absolute electricity consumption in combination with a drop in oil and gas prices induced a fuel switch: gas power plants with fewer greenhouse gas emissions increased their share in electricity generation while lignite and hard coal power plants produced less electricity compared to previous years [6–8]. Thus, the COVID-19 pandemic induced several unexpected changes in electricity systems, which in their coincidence resulted in unique and completely new circumstances in

Abbreviations: RES, Renewable Energy Sources; ENTSO-E, European Network of Transmission System Operators for Electricity; IEPN, Interconnected European Power Network.

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electricity systems.

Such an increase in the share of RES, in particular, solar and wind power plants, comes along with a general increase in intermittent electricity generation [9]. Hence, to ensure system stability, there is a growing need for various flexibility measures to balance electricity demand and supply [10,11]. There are several flexibility options that provide the required flexibility in electricity systems. These options are demand-side flexibility, sector coupling, supply-side flexibility, storages, and transmission flexibility to balance supply and demand [10,12]. In this paper, we focus on transmission flexibility and in particular the exchange of electricity via transmission lines within the power network of the European Network of Transmission System Operators for Electricity (ENTSO-E) [10,13,14].

Connecting several single European power networks – including Germany in its center –, the interconnected European power network is one of many "interconnected power networks" worldwide [2]. Such connections between various single power networks exhibit different advantages, e.g., the promotion of electricity trading across wide areas with increased competition, more diverse electricity generation schemes, and different consumption patterns [15]. The latter may allow for a better integration of intermittent RES as over-supply of, e.g., wind power in one period and in one country can be exported to a neighboring country [16,17]. Therefore, the formation of an interconnected power network generally fosters an increased security of supply [2]. Naturally, such interconnections of power networks also come along with an increase in dependencies between the respective regional power networks. An (unexpected) change in one part of the interconnected power network, i.e., in one regional power network, may therefore lead to repercussions across the entire interconnected power network [18].

Coupled electricity markets that underlie most interconnected power networks, allow to actually allocate pooled generation resources via power exchanges. Resulting electricity imports and exports carried out among these coupled market areas serve as a means to generate electricity at lower cost and, thereby, lead to cheaper electricity for customers of the interconnected power network [15].

During the COVID-19 pandemic, Germany exhibited not only an increase in share of RES, but also an increase in electricity imports. Ultimately, Germany, a net exporter of electricity over the past years, became a net importer of electricity during the COVID-19 pandemic and, therefore, relied on electricity imports from its neighboring countries [8,19]. The interconnected European power network helped to address changes associated with the COVID-19 pandemic in Germany in form of increased inter-regional electricity imports [8]. In this paper, we, therefore, aim to analyze the development of German electricity imports during the COVID-19 pandemic with regard to a market, environmental, and network perspective. Based on the increase in both the share of RES in Germany and the imports of Germany in 2020, we raise the following research question:

What can we learn from the development of German electricity imports as a flexibility option during the COVID-19 pandemic from a market, environmental, and network perspective?

To answer this research question, we first give an overview of the relevant literature in relation to our research question (cf. Section 2). Next, we describe our methodological approach by formulating three hypothesis as well as the data on electricity imports and exports. Both the hypotheses and the presented data serve as the basis to answer our research question (cf. Section 3). Our approach includes the formulation of hypothesis that serve to partition our overarching research question. Therefore, in Section 4 we analyze and test the formulated hypothesis. Finally, we discuss what we can learn from the development of electricity imports and exports during the COVID-19 pandemic from a market, environmental, and network perspective for the future (cf. Section 5 and Section 6).

2. Related work

While the COVID-19 pandemic constitutes a crisis in the health sector, it comes along with many implications for other areas of life as well. In energy-related research, existing publications already analyze the effects of the COVID-19 crisis on (a) energy systems in general and, in particular, (b) the sectors of heating/cooling and transport, as well as (c) the electricity sector.

Investigating the implications of the COVID-19 pandemic for the energy transition, Steffen et al. [20] recommend three principles for coping with such a crisis; no short-term overreacting, mid-term utilization of new opportunities for the energy transition, and long-term development of new policy designs that can sustain future shocks. Giving a review on the development of RES and sustainable energy during the COVID-19 pandemic, Hosseini [21] argues that targeted policy measures might convert the harm of the COVID-19 pandemic into a renewed focus on long-term sustainability goals in the energy sector. Jiang et al. [4] find that the impacts of the pandemic on energy demand have been substantial. The authors emphasize five categories of new opportunities stemming from the COVID-19 pandemic: enhancement of digitalization, lifestyles that exhibit lower energy usage, enhancement of resilience including circular economy, opportunities for RES and energy storage, and fighting infectious diseases and saving energy. Alvares [22] introduces a multi-objective procedure to enable the service of electricity supply in times when infections and deaths affect the personnel of power plants by the case of the Argentine power system. The procedure allows an identification of critical areas and derives corrective measures. Klemeš et al. [23] provide an overview of invested energy sources, e.g. for personal protection equipment and testing kits, and the corresponding environmental footprints during the COVID-19 pandemic. The authors find that, for instance, reusable protection equipment constitute a possibility to lower the corresponding energy consumption and therefore the environmental footprint. The results of Brosemer et al. [24] indicate that the COVID-19 pandemic stresses the importance of energy sovereignty as the right of communities to participate in decision making aiming for a just energy system. The authors state that energy sovereignty represents a critical component in a post COVID-19 energy system in order to leave no one behind.

Turning to the heating/cooling sector, Zhang et al. [25] investigate the impact of different levels of confinement measures on thermal energy demand and electricity for the case of a Swedish building mix that consists of residential buildings, schools, offices, and retail shops. In terms of the transport sector, Nižetić [26] analyzes the impact of the COVID-19 pandemic on air transportation mobility using a case study in European air transportation. The author finds that the pandemic affected air transport mobility – with a peak in reduction in the number of flights in the EU region of more than 89% –, which directly led to a reduction of CO_2 emissions. Similar, Abu-Rayash and Dincer [27] investigate mobility trends during the COVID-19 pandemic. In terms of global transportation, their results reveal a reduction of transportation that results in significant greenhouse gas reductions. Conducting a case study, Bazzana et al. [28] investigate mid-term impacts of the COVID-19 pandemic on the Italian transport and energy sector. For the transport sector the authors find that in their medium scenario (i.e., stop of emergency by the end of 2021) emissions by 2030 are 6% lower than in the pre-pandemic time.

The COVID-19 pandemic also led to altered circumstances in the electricity sector which is the focus of this paper. In this context, Zhong et al. [29] provide a comprehensive review of the impact of

COVID-19 on the electricity sector. The results of the review indicate that in many countries, electricity demand dropped, electricity consumption and load profiles changed, and the share of RES increased. Hilares et al. [30] find that such altered circumstances led to a greenhouse gas reduction of 60% in the Peruvian electricity systems. Considering, e.g., the decline in electricity consumption, Bahmanyar et al. [31] examine the impact of containment measures on electricity consumption in Europe, in particular, in Belgium, Italy, Spain, and the UK. Comparing different approaches with respect to implemented countermeasures, e.g., levels of confinement measures, the authors find that various levels of countermeasures (defining allowed and prohibited activities) affect electricity consumption profiles. Santiago et al. [32] investigate the Spanish electricity demand during the COVID-19 pandemic. Their results reveal that during the lockdown the decline in electricity demand and changes in demand profiles led to an increased share of RES in Spain. Examining the influence of the COVID-19 pandemic on national electricity systems by the example of the United Kingdom, Liu and Lin [33] establish a deep-learning-based predictive model and find, among other results, that RES will keep growing in the United Kingdom in a post-pandemic time. Krarti and Aldubyan [34] provide review analysis on the impact of stay home living patterns on energy consumption. Their results reveal that while overall electricity demand decreased due to lower demand in commercial buildings and manufacturing, energy consumption for housing increased during full lockdown periods. Abu-Rayash and Dincer [35] investigate the impact of the COVID-19 pandemic on energy-sector dynamics by analyzing data for the province of Ontario. Regarding temporal patterns of electricity consumption, the authors' results reveal that the highest electricity demand shifted from the second half of the work week (Wednesday-Friday) in a pre-pandemic time to the first half (Monday-Tuesday) in the post-pandemic time. Taking such changes in temporal patterns of electricity consumption into account, Lu et al. [36] develop an electricity consumption prediction model that results in being superior to benchmark models.

Investigating the role of flexibility during the COVID-19 pandemic, Heffron et al. [37] draw five policy recommendations with respect to flexibility in future energy systems. Generally the authors emphasize the role of flexibility as an essential element of the energy transition. Regarding the influence of COVID-19 on both CO_2 emissions and the economy, Sikarwar et al. [38] study the US, EU-28, China, and India, finding an overall economic decline for Q2 2020 and total global CO_2 emission reductions for the time period from January to April 2020. Han et al. [39] examine the reductions in CO_2 emissions in China during 2020 and find a reduction in Q1 2020 mainly due to lower coal consumption and cement production. Studying government policies and activities, Le Quéré et al. [40] find that the impact on emissions depended on the duration of confinement measures that were implemented by politicians. Summed up, the COVID-19 pandemic has led to several changes in electricity systems. So far, literature already investigates the pandemic's effect on electricity demand, electricity consumption, and load profiles respectively patterns, share of RES, and greenhouse gas emissions.

As stated, the Interconnected European Power Network (IEPN), with Germany in its center, has various advantages by combining several single European power networks. Literature already intensively investigates the usage of those advantages, e.g., diversification in electricity generation technologies or the exploitation of different consumption patterns. For the case of the China Southern Power Grid, Zhang et al. [41] investigate the potential of sharing hydropower flexibility by developing a decentralized and coordinated model. However, due to increased dependencies between the respective regional power networks, changes in one part of an interconnected power network may result in repercussions across the entire interconnected power network. Neumayer and Modiano [42] quantify the cascade effects of regional disasters on power networks and propose a new approach modeling dependencies in power networks. Addressing the challenge of increased dependencies in interconnected networks, Wu and Wang [43] present a post-disruption recovery framework. Considering imports and exports in electricity systems during the COVID-19 pandemic, Senthilkumar et al. [44] find that for the Indian electricity system, regional generation capacities increasingly met demand locally. Therefore, inter-regional exchange in terms of exports and imports greatly declined during the COVID-19 pandemic. Halbrügge et al. [6] analyze, how the German and other European electricity systems behaved during the first wave of the COVID-19 pandemic. In contrast to the Indian electricity system, Halbrügge et al. [6] reveal that during this period Germany increasingly imported electricity from its neighboring countries. Similarly, the results of Werth et al. [8] indicate that during the COVID-19 pandemic Germany as a net exporter of electricity over the past years, became a net importer of electricity from its neighboring countries.

Concluding the COVID-19 pandemic also exposed European electricity systems to altered circumstances that led to regional changes in the IEPN. Existing literature already extensively examines these changes in European electricity systems faced due to the COVID-19 pandemic. Moreover, research already addresses the increased transmission flexibility that resulted during the COVID-19 pandemic. However, research still lacks an investigation of increased electricity imports with a focus on the development of electricity prices, i.e. the market perspective, of the share of RES, i.e. the ecological perspective, and of the utilization of interconnection capacities, i.e. the network perspective.

This paper, therefore, analyzes the increased imports in Germany during the COVID-19 pandemic in view of these three perspectives during the same period.

3. Methodological approach

To address our research question, we formulate three hypotheses. These hypotheses serve to partition the overarching research question. In the following, we derive each hypothesis from the existing body of knowledge in literature (cf. Section 3.1). In order to investigate the three hypotheses, we analyze data by using descriptive statistics (cf. Section 4.1 to Section 4.3). To investigate the three hypotheses, we especially use data from the ENTSO-E Transparency Platform, which is an online open access data platform for European electricity system data [45,46]. At the end of each subsection (cf. Section 4.1 to Section 4.3), we reflect on the hypotheses considering the insights from our analysis. Finally, we discuss the results of the analyses from an integrated perspective in Section 5.

3.1. Formulation of hypotheses

Starting with the market perspective, literature generally states that with an increased share of intermittent RES electricity systems need to increase efforts to balance electricity generation and consumption at all times [12]. For this purpose, various flexibility options, e.g., demand-side flexibility, sector coupling, supply-side flexibility, storages, and grid flexibility can contribute to the required flexibility [10]. Hence, with an increase in the share of intermittent RES − as we could observe during the COVID-19 pandemic in 2020 −, there is also an increasing need for those flexibility options [6,12]. In particular, Germany made use of increased international transmission flexibility in the form of more electricity imports [8]. In economic terms, such higher demand for flexibility leads to increased prices for flexibility.

Thus, based on the basics on flexibility in electricity systems and the unique circumstances in electricity systems during the COVID-19 pandemic in the IEPN, we formulate the first hypothesis as follows.

H1. During the COVID-19 pandemic, for Germany the prices of international transmission flexibility, i.e., German electricity imports, increased.

The increased share of RES in Germany contributed to a decrease in greenhouse gas emissions [47].

As stated above, German electricity imports provided the flexibility needed under such a high share of RES [8,19]. However, the electricity generation mix of each national electricity system within the IEPN differs due to, e.g., national strategies and geographic circumstances [48]. In this regard, the question arises how German electricity imports influenced the decrease in greenhouse gas emissions in 2020. As a first step to approach this question, it is of relevance, what kind of electricity Germany imported from its neighboring countries – in other words, it is of relevance from which countries and which corresponding electricity generation technologies Germany imported. Therefore, we formulate the following hypothesis:

H2. During COVID-19, electricity imported by Germany exhibited a lower share of renewable energy than electricity generated in Germany.

For further research, it is important to also take the perspective of the IEPN, i.e., the utilization of the power network, into account. Since 2009, several national European electricity systems were progressively connected and formed the IEPN (cf. Section 1) [49]. Since then, system operators enforced an expansion of international grid capacities and thereby increased the interconnection of national European electricity systems. With increased interconnection capacities, electricity exchanges between national electricity systems increased as well [50]. An increase in electricity exchanges between national electricity systems leads to an increasing utilization of interconnection capacities at national borders. Therefore, interconnection capacities represent the limit for the flexibility option of electricity imports/exports. Hence, the utilization of interconnection capacities during the COVID-19 pandemic might indicate in which amount Germany may further amplify this flexibility option in the future. To investigate this, we hypothesize the following:

H3. During the COVID-19 pandemic, Germany's interconnection capacities in the IEPN experienced higher levels of utilization compared to previous years.

3.2. General information on data basis

We downloaded 33 GB of raw data from the ENTSO-E Transparency Platform. The data comprise the years 2015–2020 for the areas of the IEPN of the ENTSO-E.

The IEPN is constantly evolving. Therefore, the corresponding data structure is also subject to changes. Such changes for instance include the split or aggregation of bidding zones as well as new transmission lines for physical flows, which leads to the appearance of data for new/adjusted bidding zones, for example. Consequently, it is necessary to identify such changes in the data preparation and consider them in the following analyses. With regard to commercial exchange, for instance, the DE-AT-LU (German-Austrian-Luxembourgian) bidding zone was split into the DE-LU bidding zone and the AT bidding zone in October 2018. This results in additional zonal data for commercial imports/exports for Austria from this date. Hereinafter, we refer to DE-AT-LU, respectively DE-LU, as the DE-(AT)-LU bidding zone. As our paper focuses on Germany, the latter change is especially important for our analyses.

The used data categories (i.e., cross-border physical flow, scheduled commercial exchange, electricity generation) have different specifications with respect to, e.g., the corresponding regional range or time resolution as well as missing data. The category cross-border physical flow comprises data on the physical flow between countries, the category scheduled commercial exchange comprises data on the exchange between bidding zones, the category electricity generation comprises data on electricity generation within a country, the category electricity prices comprises data on Day-Ahead prices in the considered bidding zones, and the category net transfer capacities represent the available trading capacities between bidding zones. Note, that in this paper, we define the import of electricity (for commercial as well as physical) with a positive sign, whereas the export of electricity exhibits a negative sign. Regarding the corresponding regional range, which is defined as a geographical area for which the data is aggregated, we distinguish between countries and bidding zones. All data exhibit a maximum time resolution of 60 min. Some data have 15 min or 30 min time intervals. We aggregated all data that was available in 15 min or 30 min time resolution to 60 min time resolution.

Finally, we evaluate the data quality, i.e., the missing data of the corresponding data categories. Overall, we obtain nearly complete data sets with the following exceptions. There is no data available for the physical imports/exports of electricity of the ENTSO-E member countries Cyprus and Iceland, as they have no network connection to other countries. There is no generation data for Albania, Iceland, Luxembourg, and Turkey on the ENTSO-E Transparency Platform. With regard to the commercial data, we could not obtain the data for the Italian bidding zone at the border to Slovenia. Table 1 summarizes the data categories and its characteristics that we analyzed.

Given the above characteristics of the data categories, we presume the data quality as sufficient to analyze our hypothesis and answer our research question.

4. Results

In this section, we analyze and test our three hypotheses (cf. Section 3.1) that partition our overarching research question in a market, environmental, and network dimension. We use data visualization and statistics, e.g., correlation coefficients, to investigate the three hypotheses. To first put the three hypotheses into context, we analyze the impact of Germany and its neighboring countries with regard to electricity imports and exports within the IEPN. Given these insights, we analyze each hypothesis in detail (cf. Section 4.1 to Section 4.3).

Fig. 1 illustrates the commercial electricity imports and exports of 38 bidding zones of the IEPN. The bars represent the cumulative amount of imports, respectively exports, for a given bidding zone in the years between 2015 and 2020. For countries, which comprise more than one bidding zone, we sum up imports/exports of the

Table 1
Summary of data.

Data categories	Area type	Missing data
Cross-border physical flow	Country	0.99%
Scheduled commercial exchange	Bidding Zone	2.60%
Electricity generation	Country	2.36%
Electricity prices	Bidding Zone	0.69%
Net transfer capacity	Bidding Zone	3.08%

corresponding national bidding zones to foreign bidding zones. Note that an overview of all bidding zones is available in Table 6 in the appendix.

Fig. 1 further exhibits that FR exported the highest amount of electricity (112 TWh in 2015, 90 TWh in 2016, 92 TWh in 2017, 90 TWh in 2018, 85 TWh in 2019, 79 TWh in 2020) in all considered years. Concerning the absolute amount of commercial imports, Fig. 1 illustrates that IT imported the highest amount of electricity in all years, except from the year of 2020 (87 TWh in 2015, 77 TWh in 2016, 82 TWh in 2017, 48 TWh in 2018, 45 TWh in 2019). In 2020, commercial imports of DE-(AT)-LU (48 TWh in 2020 in comparison to 43 TWh for IT) were higher than the ones in IT.

Next to the commercial exchange, we also consider the physical imports/exports (cf. Section 3). Our analyses on the physical electricity imports and exports reveal that the countries with the highest absolute amount of imports and exports differ between 2015 and 2020. For all years except from one, Germany exported the most (74 TWh in 2015, 71 TWh in 2016, 76 TWh in 2017, 77 TWh in 2018, 61 TWh in 2020). In 2019, France exported the most (68 TWh in 2019 in comparison to 67 TWh for Germany). Concerning the amounts of physical import, Italy exhibited the highest amount in all years considered, again except from the years of 2015 and 2020 (39 TWh in 2016, 39 TWh in 2017, 44 TWh in 2018, 43 TWh in 2019). In 2015 and 2020, the amount of physical imports of Germany were the highest (54 TWh in 2015 in comparison to 47 TWh for Italy and 42 TWh in 2020 in comparison to 38 TWh for Italy).

Both physical flow and commercial exchange highlight the central role of Germany and its neighboring countries in the IEPN (cf. Fig. 1).

Next, we aim at investigating the increase of Germany's electricity imports during the COVID-19 pandemic. Fig. 2 illustrates the profiles for the aggregated commercial imports (cf. Fig. 2 (a))/ commercial exports (cf. Fig. 2 (b)) for the years 2015–2020 with all neighboring bidding zones of DE-(AT)-LU in each calendar week. Fig. 2 (a) indicates a growth in imports between the calendar weeks 15 and 23. In contrast, Fig. 2 (b) does not reveal visible deviations for the exports in 2020 compared to previous years.

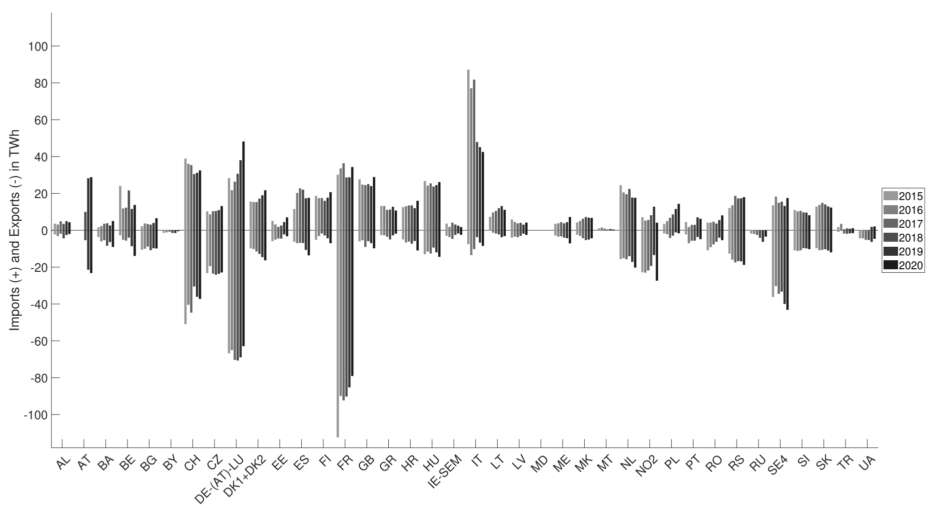
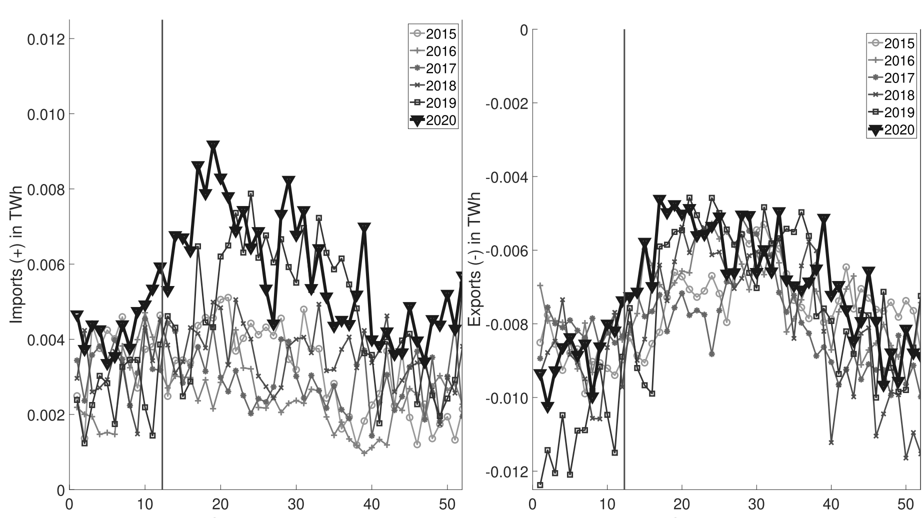


Fig. 1. Cumulative commercial imports (+) and exports (−) of 38 European bidding zones for the years 2015–2020. Own illustration, data from Ref. [51].



(a) Imports (+). (b) Exports (-).

Fig. 2. Profile for commercial imports and exports of DE-(AT)-LU for the years 2015–2020. The vertical lines represent the start of our period of interest. Own illustration, data from Ref. [51].

During spring 2020, Germany implemented countermeasures such as school and border closures to restrain the spread of the COVID-19 pandemic. On the 17th of March 2020, the German government started the first partial lockdown [6,52]. Over the course of the year, countermeasures were adjusted. Thus, in the following, we focus on the period starting with the 17th of March until the end of 2020. In Fig. 2 (a) and (b) two vertical black lines indicate our period of interest.

Given these first insights in German electricity imports and exports, we now aim at investigating how DE-(AT)-LU imported/exported electricity during the COVID-19 pandemic in comparison to previous years in a quantitative way. Table 2 summarizes key figures of Germany's electricity imports and exports for the years from 2015 to 2020. In particular, the table represents the total amount of electricity imports and exports of Germany from 2015 to 2020. Also, we calculated the relative change in electricity imports in comparison to the ones in the previous year. For 2020, German electricity imports exhibited a new record of 48.20 TWh and an increase of 26.71% in comparison to 2019.

Considering Germany's electricity imports during the COVID-19 pandemic, we can observe that Germany increasingly relied on electricity generation of other countries. In fact, Table 2 highlights the increased relevance of electricity imports of Germany from its neighboring countries in 2020 in comparison to previous years. In particular, relating the development of Germany's electricity imports to its electricity exports, in 2020 the net exports exhibit the largest relative increase. Taking these previous findings into account, in the following we focus on Germany's imports during the COVID-19 pandemic by investigating our three hypotheses.

4.1. Market perspective

From the market perspective, we formulated the hypothesis that during the COVID-19 pandemic the prices of international transmission flexibility for Germany, i.e., German electricity imports, increased.

4.1.1. General approach for the analysis of hypothesis H1

To analyze the development of prices for electricity imports and exports, we examine the differences of the electricity prices between the German bidding zone and its neighboring bidding zones. Note, that transmission between Germany and Norway as well as Germany and Belgium was only possible from the end of 2020 onwards. In particular, ALEGrO as the transmission line between Belgium and Germany, started its operation on the 9th of November 2020, and NordLink as the transmission line between Norway and Germany, started its operation on the 9th of December 2020. However, in 2020 only test runs were performed on those transmission lines. In particular, we analyze Day-Ahead prices.

4.1.2. Analysis of hypothesis H1

In Fig. 3, we visualize data from the Day-Ahead market in each of the 11 neighboring bidding zones during the COVID-19 pandemic. For every bidding zone and each year between 2015 and 2020, Fig. 3

Table 2
Electricity imports and exports Germany. Data from Ref. [51].

Year	Imports		Exports		Difference (Exports-Imports)	
	Amount	relative change	Amount	relative change	Amount	relative change
2015	28.26 TWh	n.a.	−66.78 TWh	n.a.	38.52 TWh	n.a.
2016	21.74 TWh	−23.09%	−65.02 TWh	−2.64%	43.28 TWh	12.36%
2017	26.40 TWh	21.44%	−70.36 TWh	8.21%	43.96 TWh	1.57%
2018	30.64 TWh	16.06%	−70.68 TWh	0.46%	40.04 TWh	−8.92%
2019	38.04 TWh	24.15%	−69.98 TWh	−0.99%	31.94 TWh	−20.23%
2020	48.20 TWh	26.71%	−62.88 TWh	−10.15%	14.68 TWh	−54.04%

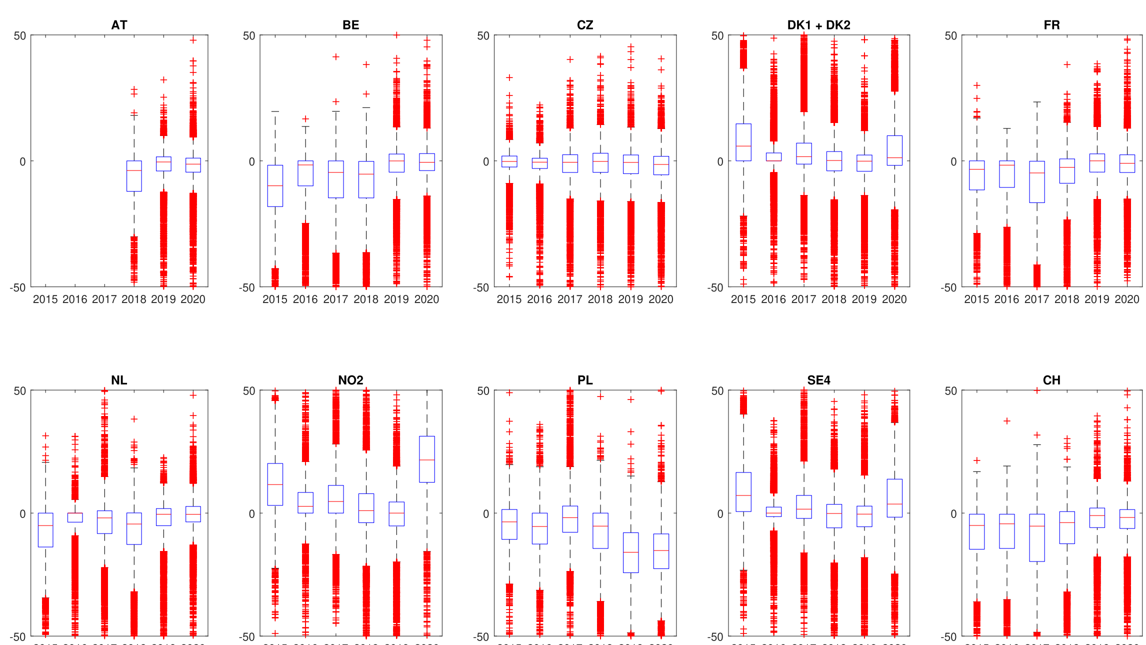


Fig. 3. Differences in electricity prices on the Day-Ahead market between Germany and its neighboring bidding zones for the years from 2015 to 2020. Own illustration, data from Ref. [51].

illustrates the hourly differences in Day-Ahead prices between Germany and its neighboring bidding zone in the form of boxplots. In particular, the plots illustrate the difference of the Day-Ahead price in Germany minus the Day-Ahead price in the neighboring bidding zone for each time step. Here, a positive sign indicates higher Day-Ahead prices and a negative sign indicates lower Day-Ahead prices in Germany.

For the Danish, the Norwegian, and Swedish bidding zones, Fig. 3 indicates an increase in scattering (cf. the height of the box) for the four bidding zones in 2020. For the Norwegian and Swedish bidding zones, the boxplots in Fig. 3 illustrate an increase in the median from 2019 to 2020 (cf. the line in the box is higher). Such an increase indicates that between 2019 and 2020, the differences in Day-Ahead prices between Germany and Norway, respectively Sweden increased, with Germany exhibiting higher prices. For the Danish bidding zones, a comparison of 2019 and 2020 illustrates that the 5 %- and 95 %-quantiles range further apart (cf. the distance between the two lines above and below the box is larger). The larger range indicates that for the Danish bidding zones the differences in Day-Ahaed prices spread wider in 2020 than in 2019. However, regarding the scattering, median, and range between the quantiles of bidding zones other than Denmark, Norway, or Sweden Fig. 3 does not reveal visible deviations for 2020.

Moreover, to investigate our hypothesis H1, not only the distribution of price differences between Germany and its neighboring bidding zones is of relevance. In addition, we need to consider at which points in time and at which corresponding price difference Germany imported which amount of electricity. Therefore, to further investigate hypothesis H1, we next weight the differences in Day-Ahead prices with the amount of imported electricity of Germany during the COVID-19 pandemic in comparison to previous years. For each bidding zone, Table 3 contains the differences in Day-Ahead electricity prices at which the bidding zone Germany/Luxembourg imported electricity, weighted by the actual amount of electricity imports. Similar to the boxplots in Table 3, positive values indicate that Day-Ahead electricity prices in Germany were higher, negative values reflect that Day-Ahead electricity prices in Germany were lower.

Table 3 does not indicate a common pattern over all years and all bidding zones. However, considering the bidding zone of Austria over all relevant years (from 2018 on), the table reveals that Germany imported — on weighted average — in times when prices in the Austrian bidding zone were higher than in the German bidding zone. A similar development can be seen in the table for France and the Netherlands (until 2019 for France and 2020 for the Netherlands).

For the Swedish bidding zone, Table 3 only contains positive values.

Hence, Germany imported electricity from the Swedish bidding zone on average in times when Day-Ahead prices in Germany are higher than in Sweden. Turning to 2020, the table indicates mostly positive values except for the ones of the Austrian and Polish bidding zones. Except for those two bidding zones, Germany on average imported in times when its Day-Ahead electricity prices were higher than the ones in the exporting countries in 2020. To specifically investigate our hypothesis H1, however, we consider the development of the values for 2020 compared to 2019. From 2019 to 2020, Table 3 exhibits a decrease in values for the bidding zones of Austria, France, Poland, and Switzerland, i.e., compared to 2019 the prices for Germany to import electricity from those bidding zones in 2020 increased. However, Table 3 also reveals an increase in values, namely for the bidding zones of the Czech Republic, Denmark, the Netherlands, and Sweden. Such an increase reflects that the prices for German electricity imports from those bidding zones in 2020 decreased compared to 2019.

4.1.3. Reflection on hypothesis H1

Turning to hypothesis H1 and considering Fig. 3 as well as Table 3, we cannot confirm that during the COVID-19 pandemic for Germany prices of international transmission flexibility in terms of electricity imports increased as in some bidding zones prices for electricity imports also decreased.

4.2. Environmental perspective

As Germany exhibited an increase in electricity imports during the COVID-19 pandemic, from an environmental perspective, we aim to examine the hypothesis, whether Germany imported electricity that exhibited a lower share of RES than the electricity generated in Germany.

4.2.1. General approach for the analysis of hypothesis H2

To examine hypothesis H2, we first investigate from which countries Germany's electricity imports actually stemmed. Then, we analyze the share of RES in the corresponding exporting countries. Note that in the following we consider RES as a composition of the following renewable generation technologies: biomass, geothermal, hydro pumped storage, hydro run, hydro water reservoir, solar, waste, wind offshore, and wind onshore. We first investigate the German share of RES in times of imports also with regard to the time slot. Then, we examine the difference in share of RES between Germany and the exporting countries. Finally, we investigate the electricity generation technologies of the exporting countries.

4.2.2. Analysis of hypothesis H2

We relate the amount of exports of Germany's corresponding exporting countries to the share of RES in the exporting country. Fig. 4 comprises eight scatterplots illustrating the absolute amount of commercial exports to Germany in comparison to their corresponding share of RES for the bidding zones of Austria, Belgium, the Czech Republic, Denmark, France, the Netherlands, Norway, Poland, Sweden, and Switzerland in 2020. Due to non-existing data in electricity generation, we did not consider Luxembourg. The black lines in Fig. 4 represent the correlation line between the amount of commercial exports and the share of RES in the exporting country. The black data point on the respective correlation line represents the average amount of exports as well as the average share of RES.

Table 3
Specific costs in EUR per MWh for electricity imports and exports of Germany for each bidding zone and each year from 2015 to 2020. Data from Ref. [51].

Year	AT	BE	CZ	DK	FR	NL	NO2	PL	SE4	CH
2015	n.a.	n.a.	0.03	10.11	−0.58	−1.80	n.a.	3.95	14.44	0.65
2016	n.a.	n.a.	0.21	3.41	−0.62	−0.43	n.a.	4.29	5.46	0.65
2017	n.a.	n.a.	−0.02	6.28	−1.94	0.86	n.a.	5.60	9.79	1.32
2018	−2.87	n.a.	0.54	3.92	−0.72	−4.46	n.a.	1.82	6.46	−0.43
2019	−0.40	n.a.	0.00	1.67	2.08	−0.17	n.a.	−1.65	6.14	1.77
2020	−1.08	0.31	0.05	7.52	2.03	2.19	22.32	−7.64	11.86	1.38

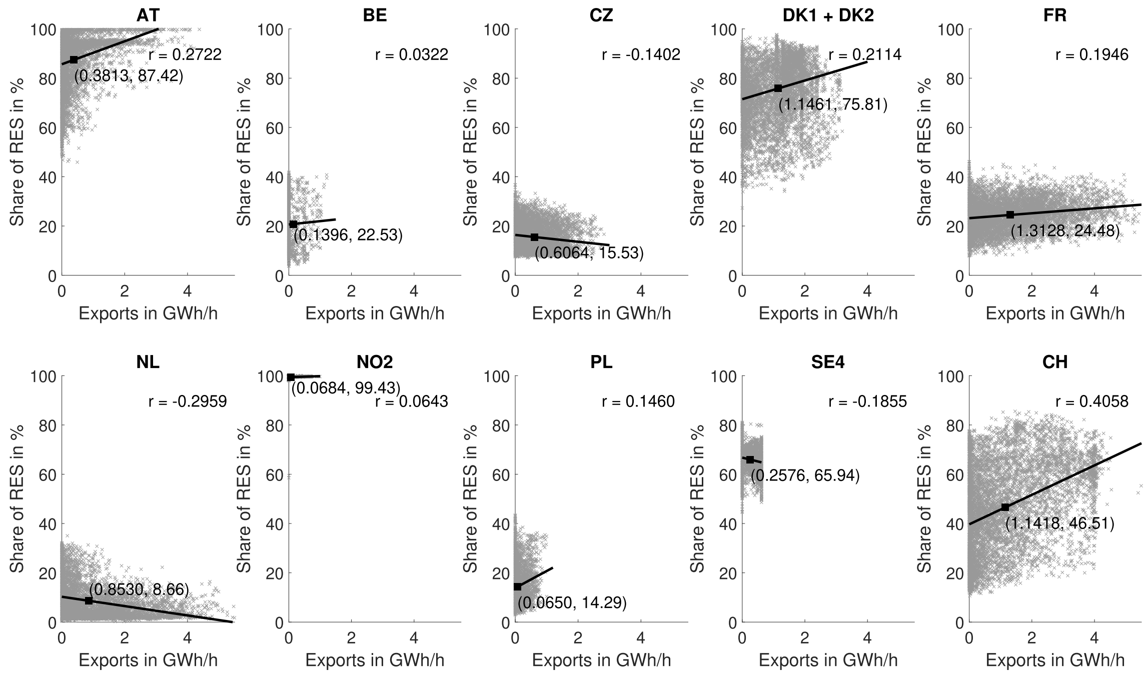


Fig. 4. Cumulative commercial exports of its neighboring countries to Germany and the corresponding share of RES in the corresponding country Own illustration, data from Refs. [51,53].

The upper part of each plot contains the correlation coefficient r between the amount of commercial exports and the share of RES.

Fig. 4 indicates that the bidding zones of Austria and Denmark in 2020 primarily exported to Germany in times when their share of RES was relatively high (87.42% for Austria and 75.81% for Denmark). Out of all bidding zones, the bidding zones of France (1.3128 GWh/h), Denmark (1.1461 GWh/h), Switzerland (1.1418 GWh/h), and the Netherlands (0.8530 GWh/h) on average exported most of commercial electricity to Germany. However, in comparison to all other bidding zones, the average share of RES for the bidding zones of France and the Netherlands was relatively low, i.e., 24.48% for France and 8.66% for the Netherlands. For seven bidding zones (AT, BE, DK, FR, NO2, PL, and CH), we can observe positive correlation coefficients, the remaining three bidding zones (CZ, NL, and SE4) exhibit negative correlation coefficients. The correlation coefficient for Switzerland, Austria, and Denmark exhibit the most positive values, i.e., 0.4058, 0.2722, and 0.2114. With a value of −0.2959 the correlation coefficient of the bidding zone of the Netherlands exhibits the lowest value.

Analogous to Fig. 4, Fig. 5 illustrates the physical exports of Germany's neighboring countries. In line with our approach, regardless of the kind of exports that we analyze – commercial or physical – there is no difference in the share of RES of the corresponding countries. Consequently, equally to commercial exports, Fig. 5 indicates the highest average share of RES for Austria and Denmark. In comparison to the other countries, France, the Netherlands, and Switzerland on average exported most of physical electricity to Germany.

In particular, Fig. 5 reveals average 1.3804 GWh/h of physical exports for France, 0.7140 GWh/h for Denmark, 0.8336 GWh/h for Switzerland, and 0.9291 GWh/h for the Netherlands. Due to identical shares of RES for commercial and physical exports, again, in comparison to the other countries, the average share of RES for France and the Netherlands was relatively low. Similar to commercial exports, for physical exports, we can observe positive correlation coefficients for six countries (Austria, Denmark, France, Norway, Poland, and Switzerland) and negative correlation coefficients for the remaining four (Belgium, Czech Republic, Netherlands, and Sweden). Note that for Belgium the sign of the correlation coefficient changes from commercial to physical exports. The correlation coefficient for Switzerland and Austria exhibit the most positive values, i.e., 0.3878 and 0.3764. With a value of −0.3597 the correlation coefficient of the Czech Republic has the lowest value.

Interpreting the analyses of exports of Germany's neighboring countries to Germany, both the commercial and the physical exports indicate that Austria and Denmark primarily exported to Germany in times of a high share of RES in their electricity systems. However, Denmark exhibits a difference in the amount of commercial (1.1461 GWh/h) and physical (0.7140 GWh/h) exports. Consequently, commercial exports from Denmark to Germany exceeded the actual physical flow. This might result from the relatively high share of RES in Denmark (75.81%) – which in the case of Denmark to a large part stemmed from wind onshore and offshore power – during our period of interest and, therefore, lower electricity prices, which might incentivize commercial exchange. For Poland, commercial exports (0.0650 GWh/h) exceeded physical exports (0.0012 GWh/h). Such differences might be due to phase shifting transformers installed at the transmission lines between Germany and Poland. These phase shifting transformers regulate the physical flow between these two countries. Turning to the individual correlations between the share of RES and the corresponding amount of export, the negative values for the Czech Republic, the Netherlands, and Sweden reveal that with a decreasing share of RES in those countries the amount of exported electricity to Germany increases. For instance, for the Czech Republic, such a negative correlation might stem from the Czech generation mix, which is mainly characterized by coal-fired power plants. The high positive correlation values for Switzerland and Austria indicate that with an increase in the share of RES, the amount of exported electricity to Germany in those countries increases. This might stem from price incentives for electricity, e.g.,

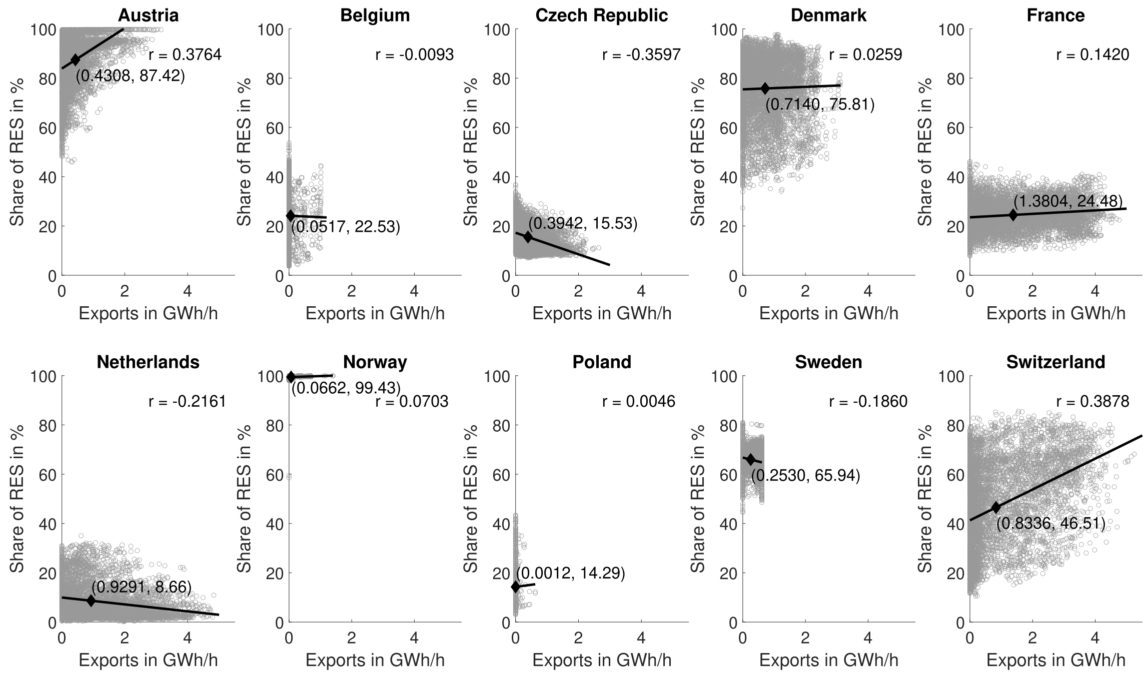


Fig. 5. Cumulative physical exports of its neighboring countries to Germany and the corresponding share of RES in the corresponding country. Own illustration, data from Refs. [53,54].

from hydro power plants, in those countries to generate electricity and sell it to Germany. Finally, Figs. 4 and 5 reveal that in 2020 Germany primarily imported electricity from countries with a relatively low share of RES, namely, France, the Netherlands, and Switzerland. Moreover, we can observe that Germany bought Danish electricity from wind power plants, but instead physically imported nuclear power from Switzerland. Such differences might be due to price signals induced by decreasing electricity prices in Denmark that stem from an oversupply of wind power in Denmark and a utilized transmission line between Denmark and Germany.

In the following, we first analyze Germany's imports in relation to its own share of RES for the years from 2015 to 2020. Fig. 6 comprises scatterplots that illustrate the sum of hourly commercial electricity imports of DE-(AT)-LU from all neighboring bidding zones and the corresponding share of RES for the years from 2015 to 2020. The black lines represent the correlation between the amount of commercial imports and the share of RES of DE-(AT)-LU. The black data points on the correlation line indicate the average amount of commercial imports as well as the average share of RES. The upper part of each plot contains the correlation coefficient

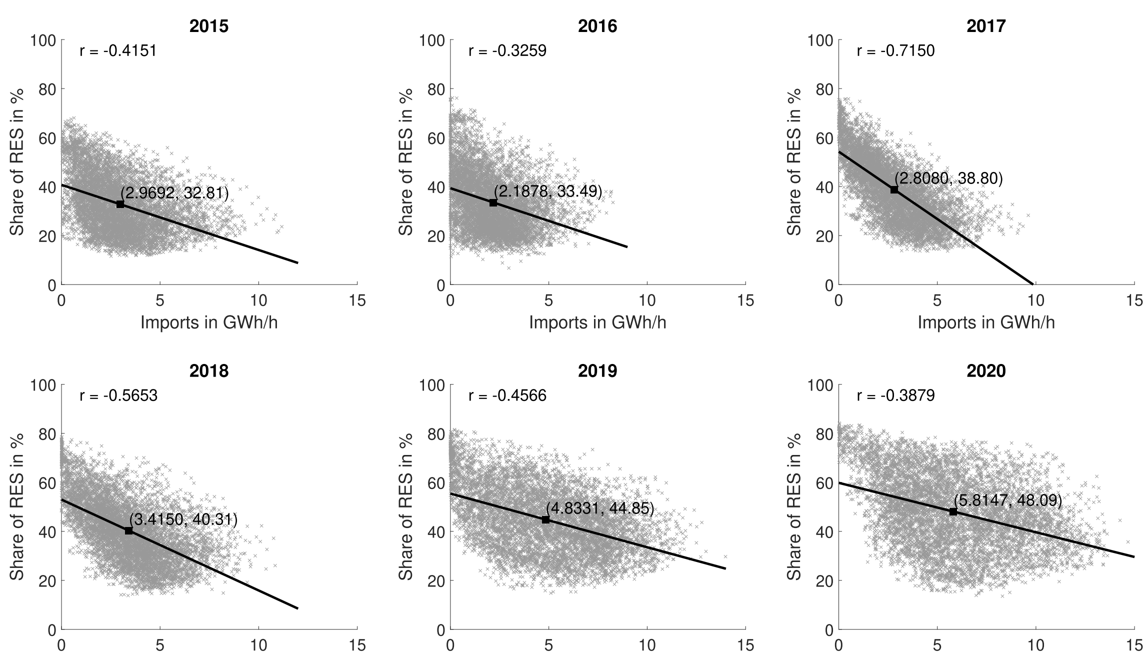


Fig. 6. Cumulative commercial exchange imports and the corresponding share of RES of DE-(AT)-LU for the years 2015–2020. Own illustration, data from Refs. [51,53].

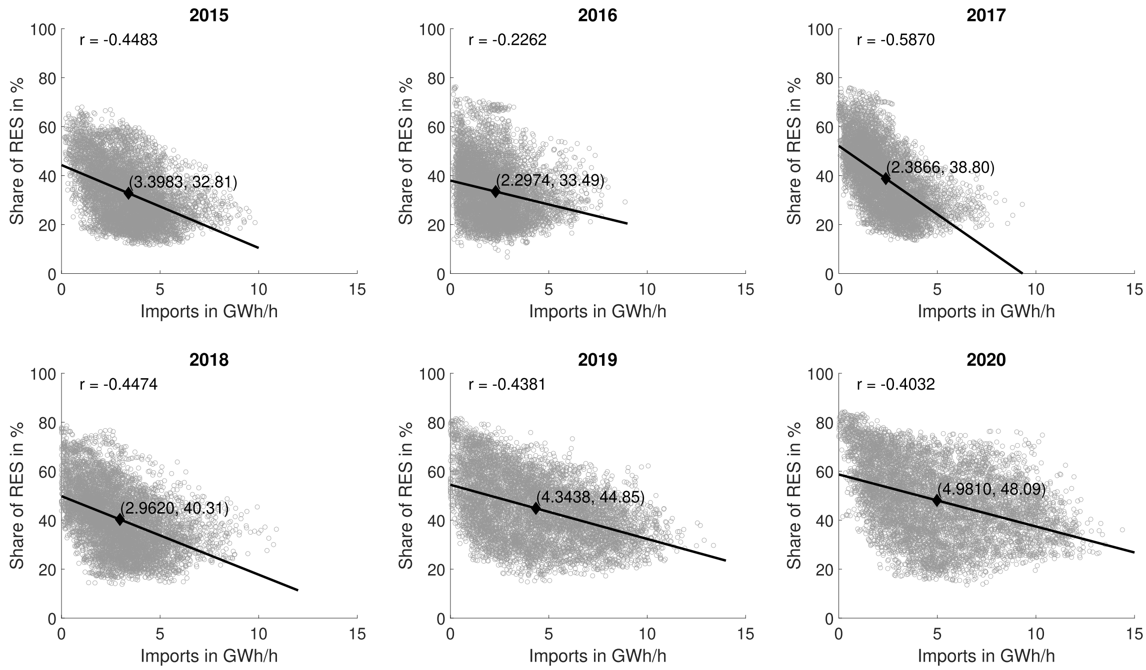


Fig. 7. Cumulative physical flow imports and the corresponding share of RES of Germany for the years 2015–2020. Own illustration, data from Refs. [53,54].

between the absolute amount of commercial imports and the share of RES.

For the years from 2016 until 2020, the plots in Fig. 6 generally indicate an increase in commercial imports as well as an increase in the share of RES. In particular, on average commercial imports of DE-(AT)-LU increase as follows: 2.1878 GWh/h in 2016, 2.8080 GWh/h in 2017, 3.4150 GWh/h in 2018, 4.8331 GWh/h in 2019, and 5.8147 GWh/h in 2020. For all considered years, Fig. 6 illustrates negative values for the correlation between Germany's absolute amount of commercial import and the share of RES. Except from 2016, Fig. 6 exhibits the least negative correlation value for the year 2020, i.e., the negative correlation between the absolute amount of commercial imports and the share of RES decreased.

Analogous to Fig. 6, Fig. 7 illustrates the sum of hourly physical electricity imports of Germany from all neighboring countries and the corresponding share of RES for the years from 2015 to 2020.

Similar to commercial electricity imports, from 2016 until 2020 the plots in Fig. 7 generally indicate an increase in physical imports as well as an increase in the share of RES. Again, for all years, Fig. 7 gives negative values for the correlation between Germany's amount of physical imports and the share of RES. Similar to commercial imports for the year 2020, Fig. 7 exhibits the least negative

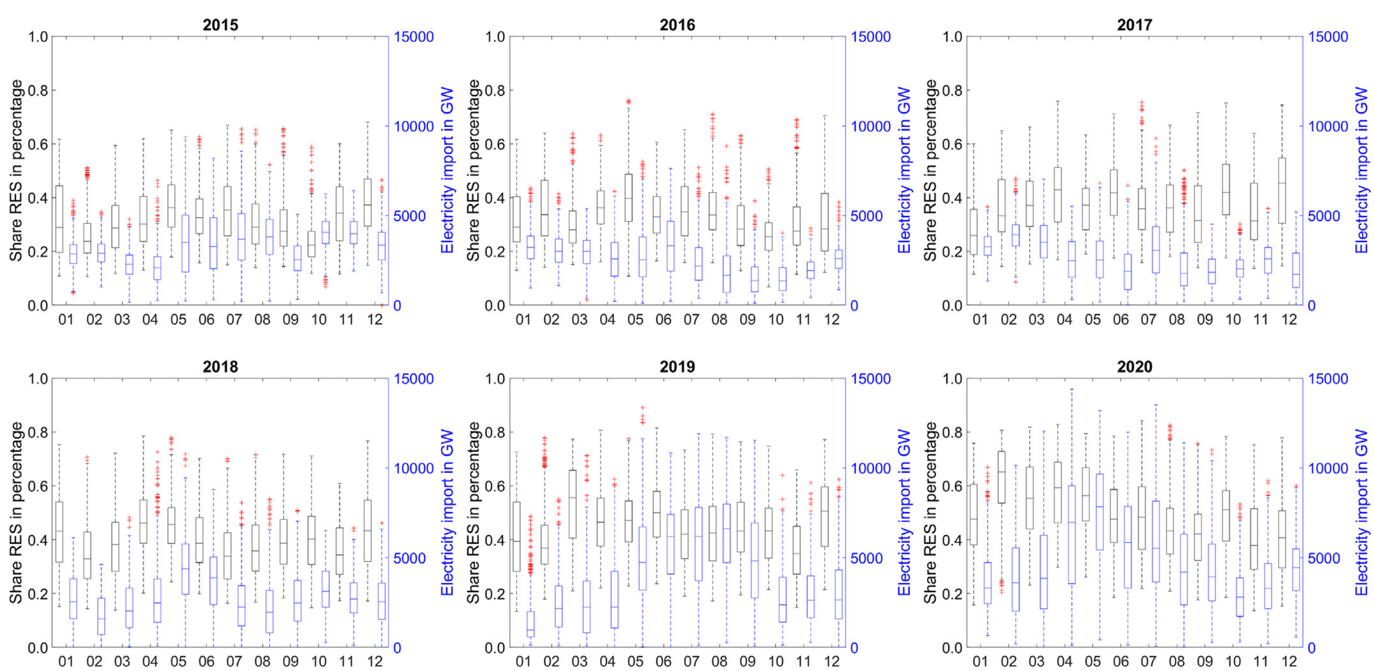


Fig. 8. Monthly German share of RES and cumulative physical flow imports. Own illustration, data from Refs. [53,54].

correlation value of all years – except for the year 2016.

An important factor in electricity generation from intermittent RES is the dependence on the time frame. In order to analyze this influencing factor, we consider the relationship between the level of German electricity imports and the German share of RES. Here, we first look at monthly sequences before we look at the correlation over the course of the day, i.e., hourly sequences.

Fig. 8 represents the German share of RES and the amount of German electricity imports for the years 2015–2020 on a monthly basis as box plots. On the primary axis we illustrate the share of RES in percentage. On the secondary axis we illustrate the cumulative amount of electricity imports in GW for 1 h. Fig. 8 indicates that from 2015 to 2020 the share of RES in Germany increased. For electricity imports, the figure indicates that during the winter months (November until January) as well as during the summer months (May until August) electricity imports increase. However, regarding the difference between 2020 and the previous years, besides the increased share of RES, we can not observe noticeable deviations. Regarding the relationship between the share of RES and the amount of electricity imports, Fig. 8 already indicates that on a monthly basis, both numbers evolve in opposite directions, i.e., with an increase in share of RES electricity imports tend to decrease.

In order to analyze these observations in more detail, we next focus on the monthly correlation coefficient between the share of RES and the amount of imported electricity. Table 4 illustrates the correlation coefficients between the share of RES and the amount of imported electricity in Germany on a monthly basis for the years from 2015 to 2020.

For most of the years and most of the months the correlation coefficient between the share of RES and the electricity imports is negative. However, Table 4 indicates that 2020 is the only year with exclusively negative correlation values.

The negative correlation values in Table 4 indicate that especially in 2020 in months with high share of RES Germany imported fewer electricity. Next, we analyze the influence relation between the share of RES and electricity imports on an hourly basis.

Fig. 9 represents the daily patterns of the share of German RES and the amount of German electricity imports for the years 2015–2020 as box plots. Similar to the monthly analysis, on the primary axis we again illustrate the share of RES in percentage, on the secondary axis we illustrate the cumulative amount of electricity import in GW. Just as Fig. 8, Fig. 9 indicates that from 2015 to 2020 the level of share of RES in Germany increased. For all years considered, around noon (11–15 o'clock) the share of RES increases and the amount of electricity imports decreases. Similar to the analysis on a monthly basis, regarding the difference between 2020 and the previous years, we cannot observe noticeable deviations. Regarding the relationship between the share of RES and the electricity imports, Fig. 9 indicates that also for the daily analysis, the share of RES and amount of electricity imports evolve in opposite directions, i.e., with an increase in share of RES electricity imports decrease.

To deepen our observations from Fig. 9, we analyze the hourly correlation coefficient between the share of RES and the amount of imported electricity. Table 5 illustrates the correlations coefficients between the share of RES and the amount of imported electricity in Germany for each hour during the day and the years from 2015 to 2020.

Table 4
Correlation coefficient of monthly German share of RES and cumulative electricity imports.

Month	2015	2016	2017	2018	2019	2020
January	−0.34	−0.20	−0.32	−0.81	−0.59	−0.28
February	−0.41	−0.36	−0.46	−0.20	−0.33	−0.44
March	−0.31	−0.48	−0.01	0.07	−0.30	−0.11
April	−0.24	−0.15	−0.49	−0.07	−0.04	−0.34
May	0.10	−0.16	0.11	0.11	0.10	−0.40
June	−0.37	0.14	−0.53	−0.59	−0.76	−0.21
July	−0.05	−0.21	0.12	0.08	−0.06	−0.61
August	−0.52	0.12	−0.40	−0.44	−0.42	−0.25
September	0.17	−0.43	−0.15	0.15	−0.15	−0.56
October	−0.25	−0.25	−0.34	−0.46	−0.34	−0.15
November	−0.01	0.06	−0.34	−0.20	−0.08	−0.45
December	−0.38	−0.31	−0.66	−0.31	−0.30	−0.06

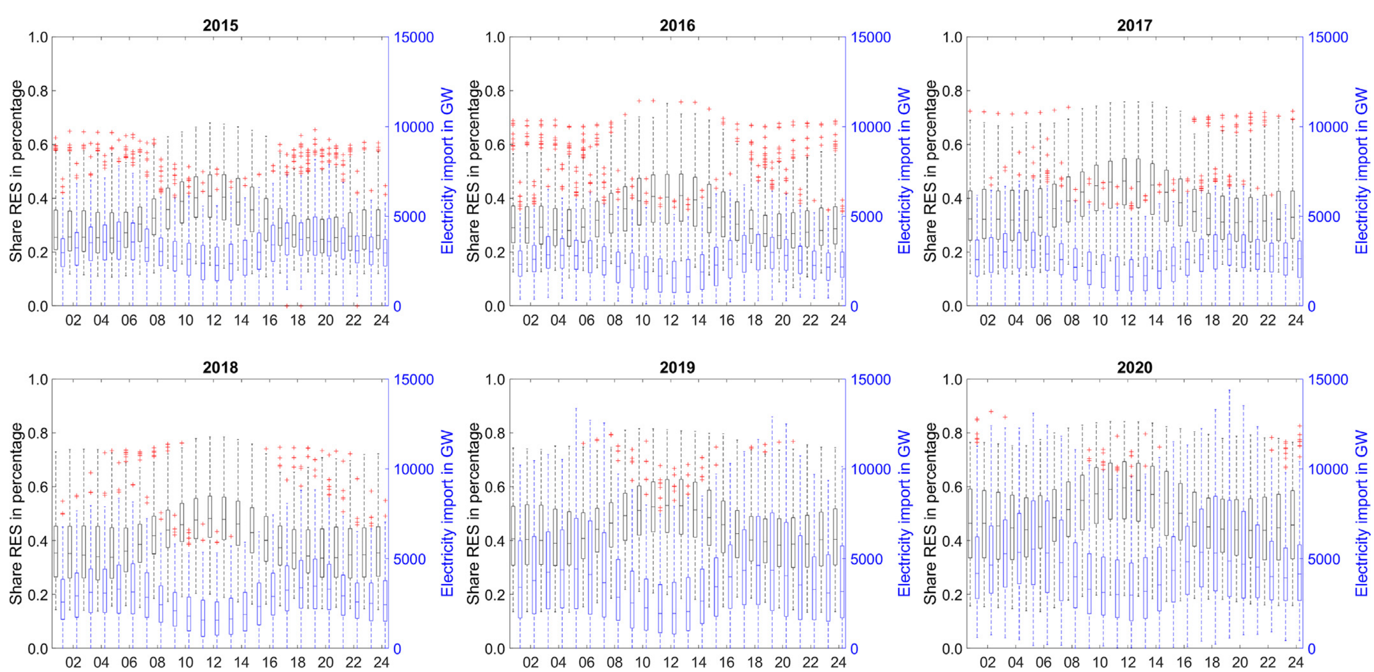


Fig. 9. Daily German share of RES and cumulative physical flow imports. Own illustration, data from Refs. [53,54].

Table 5
Correlation coefficient of hourly German share of RES and cumulative electricity imports.

Hour	2015	2016	2017	2018	2019	2020
1	−0.37	−0.24	−0.61	−0.46	−0.42	−0.54
2	−0.36	−0.24	−0.62	−0.44	−0.42	−0.57
3	−0.35	−0.23	−0.61	−0.41	−0.42	−0.57
4	−0.33	−0.18	−0.58	−0.37	−0.42	−0.55
5	−0.29	−0.15	−0.55	−0.38	−0.38	−0.51
6	−0.24	−0.09	−0.47	−0.37	−0.29	−0.40
7	−0.21	−0.07	−0.43	−0.32	−0.25	−0.29
8	−0.25	−0.17	−0.47	−0.28	−0.23	−0.28
9	−0.30	−0.26	−0.51	−0.28	−0.21	−0.26
10	−0.38	−0.28	−0.55	−0.33	−0.24	−0.25
11	−0.47	−0.36	−0.59	−0.42	−0.29	−0.29
12	−0.48	−0.29	−0.59	−0.42	−0.28	−0.28
13	−0.51	−0.31	−0.57	−0.42	−0.28	−0.30
14	−0.51	−0.25	−0.54	−0.42	−0.26	−0.29
15	−0.49	−0.18	−0.50	−0.40	−0.26	−0.27
16	−0.39	−0.09	−0.46	−0.33	−0.29	−0.29
17	−0.23	−0.02	−0.42	−0.31	−0.37	−0.31
18	−0.19	−0.01	−0.46	−0.34	−0.43	−0.35
19	−0.25	−0.01	−0.49	−0.40	−0.47	−0.39
20	−0.24	−0.04	−0.47	−0.39	−0.48	−0.41
21	−0.24	−0.06	−0.48	−0.39	−0.50	−0.41
22	−0.28	−0.15	−0.52	−0.41	−0.52	−0.45
23	−0.35	−0.27	−0.57	−0.46	−0.45	−0.48
24	−0.39	−0.25	−0.60	−0.45	−0.42	−0.52

For most of the years and most of the hours, the correlation coefficient between the share of RES and the electricity imports is negative.

Given these insights on Germany's development of electricity imports in relation to the corresponding monthly respectively daily share of RES, we now deepen our analyses with regard to the difference in share of RES of the exporting countries and the German share of RES. Note, that for the country specific electricity generation mix for each time step we calculate the average of all producing electricity generation technologies.

Fig. 10 illustrates the amount of commercial imports (cf. Fig. 10 (a)) and physical imports (cf. Fig. 10 (b)) and relates it to the corresponding difference in the share of RES between Germany and the amount-weighted share of RES of all exporting countries. More specifically, the x-axis gives the share of RES in Germany minus the weighted share of RES in all exporting countries. A negative x-axis-value, illustrates that at this point in time the share of RES in Germany was lower than the weighted-average in the exporting countries. A positive x-axis-value implies that at this time the share of RES in Germany was higher than the weighted-average in the exporting countries.

For both kinds of imports, commercial and physical, the black points on the left, respectively right hand side of the vertical line represent the corresponding average share of RES and the average amount of imports. The point on the left side represents the average imports and average difference in RES share when Germany had a lower share of RES compared to the exporting countries and vice versa. Also, right below these points, the data labeling gives the number of considered data points on the left, respectively right hand side.

Given the results of our analyses in Figs. 6 and 7, the negative correlation coefficients for all years indicate that in all years from 2015 to 2020 a decrease in the share of RES led to an increase in amount of commercial as well as physical electricity imports. As – except from the year 2016 – the correlation coefficient for 2020 was the least negative, during the COVID-19 pandemic Germany's commercial and physical electricity imports increased also in times when the share of RES was relatively high. Hence, Germany increasingly relied on electricity imports, even in times of a large share of RES.

Interpreting the results of our comparison between the German share of RES and the share of RES in the corresponding exporting country (cf. Fig. 10), both the commercial and the physical imports reveal that a large amount of Germany's electricity imports stemmed from countries with a lower share of RES than the German one. Consequently, on average, Germany imported electricity which exhibited a lower share of RES.

As Germany's neighboring countries comprise a variety of electricity generation technologies, next, we seek to derive further insights on the question which technologies generated the imported electricity.

Fig. 11 illustrates the four main electricity generation technologies and the cumulative amount of the remaining electricity generation technologies of the bidding zones of Austria, Belgium, the Czech Republic, Denmark, France, the Netherlands, Norway, Poland, Sweden, and Switzerland related to the amount of commercial exports to Germany during the COVID-19 pandemic in 2020.

The analyses already reveal that France, Denmark, the Netherlands, and Switzerland constitute a large amount of commercial exports to Germany. More specifically, Fig. 11 indicates that during the COVID-19 pandemic, nuclear power from France (15.44% of the total German imports) and Switzerland (12.12%), gas (7.62%) and other conventional (4.16%) power from the Netherlands, wind onshore (6.61%) and offshore (4.61%) power from Denmark, and hydroelectric power from France (3.25%) and Switzerland (6.26%) primarily provided Germany with electricity.

Fig. 12 illustrates the four main electricity generation technologies and the cumulative amount of the remaining electricity generation technologies of Austria, Belgium, the Czech Republic, Denmark, France, the Netherlands, Norway, Poland, Sweden, and Switzerland in relation to the amount of physical exports to

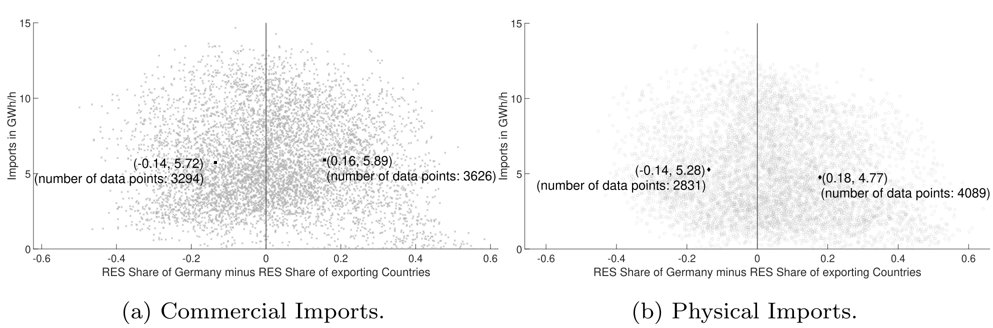


Fig. 10. Difference in share of RES between Germany and the corresponding exporting countries for all points in time of imports in Germany. Own illustration, data from Refs. [51,53,54].

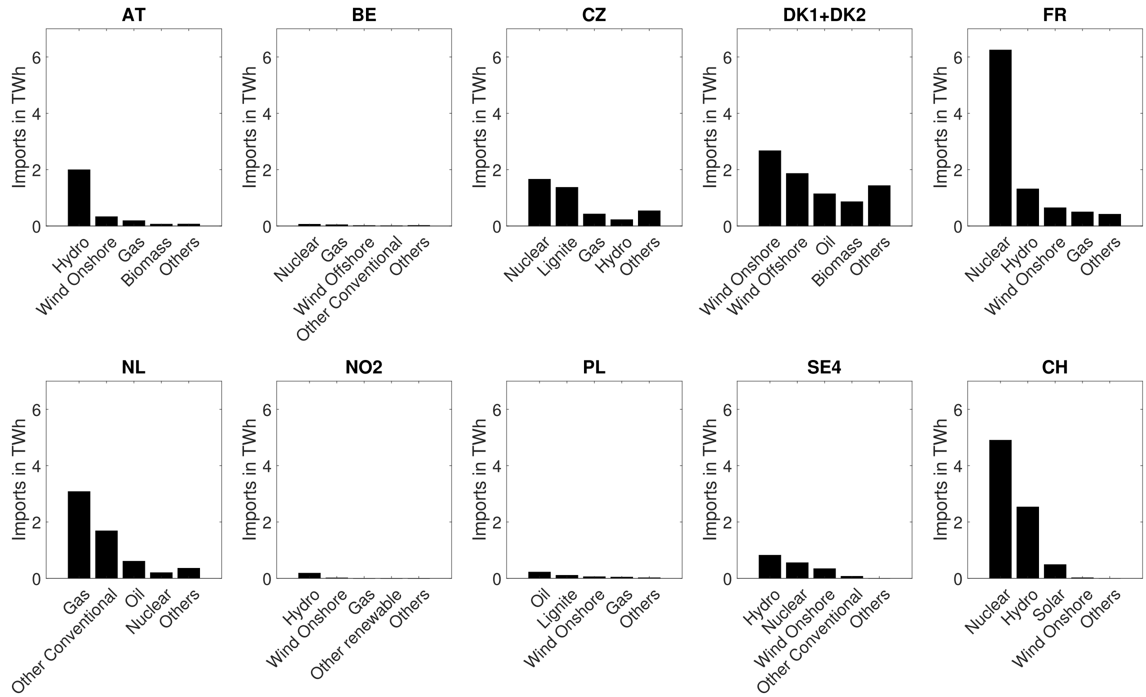


Fig. 11. Commercial exports of its neighboring countries to Germany sorted by their four leading electricity generation technologies. Own illustration, data from Refs. [51,53].

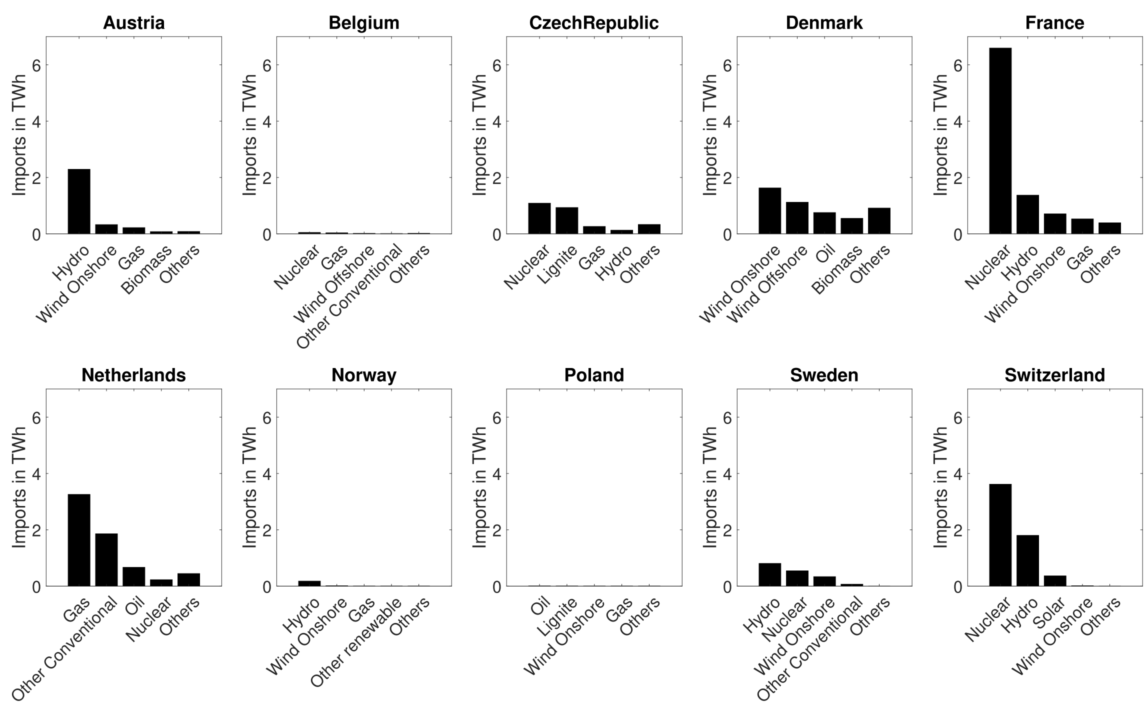


Fig. 12. Physical exports of its neighboring countries to Germany sorted by their four leading electricity generation technologies. Own illustration, data from Refs. [53,54].

Germany during the COVID-19 pandemic in 2020. Again, nuclear power from France (19.03%) and Switzerland (10.44%), gas (9.40%) and other conventional (5.37%) power from the Netherlands as well as hydroelectric power from Austria (6.61%) and Switzerland (5.20%) primarily supplied Germany with electricity.

Both figures for commercial as well as physical exports reveal that during the COVID-19 pandemic in 2020 Germany, in particular, imported electricity from French and Swiss nuclear power plants. Moreover, our analyses illustrate that during this period Germany relied on electricity imports from gas and other conventional electricity generation technologies from the Netherlands. Based on our analyses of the foreign electricity generation technologies, we also observe some differences in commercial and physical exports. For instance, the amount of physical exports of French and Swiss nuclear power exceeds that of commercial exports. In contrast, for Denmark, commercial exports based on wind on- and offshore exceed physical exports of wind on- and offshore. Such a difference might result from low electricity prices that stem from larger shares of RES.

4.2.3. Reflection on hypothesis H2

Turning to hypothesis H2, we find that during the COVID-19 pandemic, Germany primarily imported electricity from countries that exhibited a lower share of RES. In particular, during the COVID-19 pandemic Germany relied on electricity imports from French and Swiss nuclear power plants, as well as gas and other conventional electricity generation technologies from the Netherlands.

4.3. Network perspective

An increase in German electricity imports comes along with an increase in (physical) exchange across national borders. To take the perspective of the IEPN into account, we next examine hypothesis H3 and investigate whether during the COVID-19 pandemic interconnection capacities of the IEPN experienced higher levels of utilization compared to previous years.

4.3.1. General approach for the analysis of hypothesis H3

For our analyses we use data on the physical border flows in relation to the net transfer capacities of each interconnection capacity. Since the physical interconnection capacity depends on, e.g., maintenance, the actual available capacity falls below the installed physical capacity. Therefore, we use the net transfer capacity that represents the available capacity for the commercial exchange between Germany and its neighboring bidding zones. To investigate hypothesis H3, we analyze the utilization of the interconnection capacities of Germany from 2015 to 2020.

4.3.2. Analysis of hypothesis H3

Fig. 13 illustrates the utilization of the interconnection capacities as heat-maps, one for each country exporting to Germany. The x-axis represents the years from 2015 to 2020, the y-axis the time in day for 24 h. As we relate the physical border flows to the net transfer capacities, the utilization illustrated as the shade of color in Fig. 13 can exceed 100%. Therefore, we use a scale from −2 to 2 in order to represent the utilization. Positive values represented by a light shade indicate times of German electricity imports, negative values represented by dark shades indicate times of German electricity exports. Due to the split of the DE-AT-LU bidding zone in October 2018, values for interconnection capacities between Germany and Austria only exist from that date. Thus, the Austrian heat map in Fig. 13 only contains data from October 2018 to the end of 2020.

For Switzerland, Fig. 13 indicates seasonal patterns during the course of the years – during summer, Germany imported electricity from Switzerland, whereas during winter the interconnection capacities exhibit higher utilization in the direction from Germany to Switzerland. Comparing the development of the interconnection capacity utilization in 2020 with previous years, the heatmaps indicate that import interconnection capacities increased at the beginning of 2020 (cf. brighter lines for, e.g., France and the Netherlands), but also decreased again over the course of the year.

To deepen this analysis on the interconnection capacities, we next consider the German interconnection capacity utilization directly comparing it to previous years. Fig. 14 illustrates the daily minimum and maximum of Germany's interconnection capacity utilization. Negative values represent times of German electricity exports, positive values times of German electricity imports. The filled areas represent the range of daily maxima, i.e., the maximum import, respectively the minimum export, for the years 2015–2019. The line represents the development of the daily maximum for the year of 2020.

Overall, Fig. 14 indicates that the utilization of interconnection capacities of Germany varies a lot depending on the exporting country. For the Czech Republic, e.g., except for a few exceptions interconnection capacity utilization remains in the range between 1 and -1. For Denmark, France, and Sweden, however, daily maxima from 2015 to 2019 as well as the values for 2020 mostly appear in the positive range. Comparing the values for 2020, Fig. 14 indicates that the interconnection capacity utilization for France, the

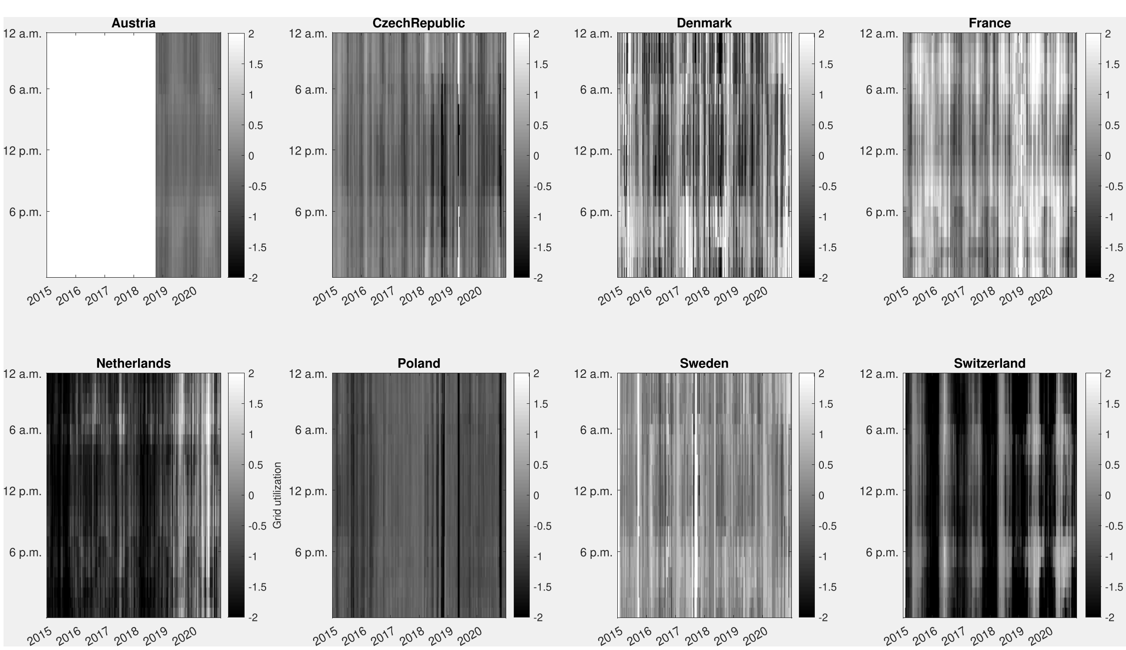


Fig. 13. Heatmaps for the utilization of Germany's interconnection capacities from 2015 to 2020. Own illustration, data from Refs. [53,54].

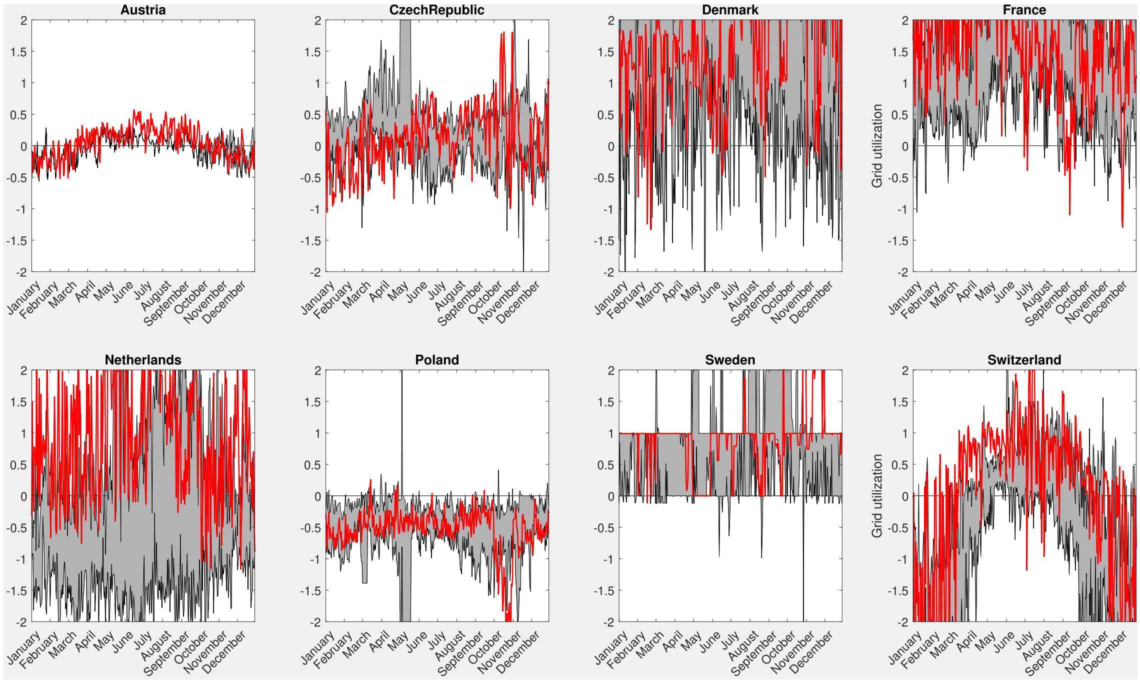


Fig. 14. Daily maximum of interconnection capacities utilization of Germany from 2015 to 2020. Own illustration, data from Refs. [53,54].

Netherlands, and Switzerland exceeded the development of previous years, especially in the beginning of the year.

4.3.3. Reflection on hypothesis H3

Turning to hypothesis H3, our analyses reveal that not for all but for some countries, i.e., France, the Netherlands, and Switzerland, Germany's interconnection capacities in the IEPN experienced higher levels of utilization during the COVID-19 pandemic compared to previous years.

5. Discussion

Based on our results regarding our three hypotheses in the previous Section, in the following, we summarize our findings on electricity imports of Germany during the COVID-19 pandemic in 2020 and discuss our research question.

Within the IEPN, Germany and its neighboring countries have a geographic central role. Moreover, Germany and its neighboring countries account for a high proportion of European imports and exports. Such a position in an interconnected network together with altered and previously unknown circumstances in 2020 may hold potential to learn from. During the COVID-19 pandemic, Germany increasingly relied on electricity imports from its neighboring countries (cf. Section 4). Such an increase in transmission flexibility might have an impact on Germany's electricity system from a market, environmental as well as network perspective. From a market perspective, our investigation rejects the hypothesis that during the COVID-19 pandemic for Germany the prices of international transmission flexibility, i.e., electricity imports, increased. More specifically, for some bidding zones, prices for German electricity imports even decreased compared to 2019 (cf. Section 4.1). Depending on their individually altered conditions within the IEPN different European bidding zones responded differently to the pandemic. Therefore, from a market perspective it is important to consider the countries' individual circumstances and the advantages resulting from the diversity of an interconnected network. From an ecological perspective, during the COVID-19 pandemic Germany primarily imported electricity from countries with a relatively low share of RES, namely France, the Netherlands, and Switzerland (cf. Section 4.2). In the past, i.e., since 2016, Germany, especially, imported electricity in times when the German share of RES was low. We can observe this relation in monthly sequences as well as in hourly sequences. However, for the time of the COVID-19 pandemic in 2020, our results reveal that Germany increasingly imported electricity in times when the German share of RES was relatively high (cf. Section 4.2). More specifically, as mentioned above, Germany's electricity imports stemmed from countries with a lower share of RES than the German share. Turning to the actual electricity generation technologies prevailing in times of imports, during the COVID-19 pandemic, Germany, in particular, relied on electricity imports from nuclear power from France and Switzerland. For physical imports the effect of Germany relying on nuclear power from France and Switzerland holds even more as compared to commercial imports (cf. Section 4.2). Consequently, during the COVID-19 pandemic Germany increasingly relied on electricity imports from countries that exhibited a lower share of RES. Thus, during this time, Germany made use of the diversity of the IEPN by importing electricity from, e.g., Swiss and French nuclear power plants or Dutch gas electricity generation technologies. From a network perspective, some interconnection capacities between Germany and other countries of the IEPN experienced higher levels of utilization compared to previous years (cf. Section 4.3). In particular, the French, Dutch, and Swiss interconnection capacities experienced higher levels of utilization. Thus, Germany increasingly relied on some of its interconnection capacities within the IEPN. In the future, such international network capacities might further gain in relevance in order to make use of the diversity of such networks.

In order to consider loop flows, we analyzed the two data categories commercial and physical imports/exports. Our corresponding analyses on both data categories reveal that for Denmark, commercial exports exceed physical exports. In other words, the commercial exchange between Germany and Denmark reflects the trading activities as a reaction to price signals between these two bidding zones. The network's physical characteristics might not allow for a physical flow of electricity that was commercially exchanged between the bidding zones of Denmark and Germany. Contrarily, for Switzerland, physical exports to Germany exceed commercial exports. Here, higher electricity prices might inhibit commercial exchange. Next to market-driven causes, physical causes like phase shifting transformers between Germany and Poland might also result in a difference between commercial and physical imports/exports. However, deviations between commercial and physical imports/exports only appear in those few aspects and our results of the two import/export categories result in the same general findings.

In 2020, Germany exhibited an increased share of RES, but also an increase in electricity imports from its neighboring countries. Consequently, having a high share of RES, Germany increasingly relied on the interconnected European power network during the COVID-19 pandemic. In a post COVID-19 pandemic period, though, electricity consumption as well as other corresponding changes in the electricity system are expected to return to conditions of a pre COVID-19 pandemic period. Nevertheless, turning to transmission flexibility, also in a post COVID-19 pandemic period Germany will still be able to import electricity from its neighboring countries that might, thereby, allow a high share of RES in Germany. In general, Germany relied on electricity imports from its neighboring countries might be reproducible. However, the fact that Germany will shut down all of its own nuclear power plants by the end of 2022 on the one hand and import foreign nuclear power on the other may be debatable. On the one hand, for building a sustainable future without the use of nuclear power plants, Germany might need to reflect on its importing behavior during and after the COVID-19 pandemic. On the other hand, in the future, not only the German but many European electricity systems will experience an increase in their share of RES. Germany might then not be able to rely on imports from foreign nuclear and renewable power plants as other countries might also need to import electricity to compensate for their fluctuating electricity generation by RES. Also, during the COVID-19 pandemic some interconnection capacities already experienced higher levels of utilization. Considering an increase in use of the IEPN in the future, Germany might reach the limits of other interconnection capacities and thus no longer be able to fully make use of this flexibility option, i.e., transmission flexibility. Ultimately, our analyses emphasize the value of a holistic view on the IEPN. Joint European policies should take system-wide effects and dependencies into account, also with regard to a sustainable development of the different national electricity systems and their speed. National strategies, which today are often coordinated with other European countries only to a limited extent, could result in a lack of the required flexibility to ensure the balance of electricity generation and consumption in the whole interconnected European power network, e.g., if many countries phase out conventional power plants that supply flexibility at the same time. Thus, individual national electricity systems may not be able to achieve a sustainable electricity system. To avoid this, an increased alignment of national strategies within Europe to jointly achieve increasing share of RES seems to be a key.

6. Conclusion and outlook

Various nations worldwide promote an increasing share of renewables within electricity generation mixes. In 2020, the German share of intermittent renewable electricity generation rose to 50.5%, i.e., an increase of 4.5% points compared to 2019. However, due to the COVID-19 pandemic in 2020 special circumstances of reduced economic activities occurred in Germany and affected the electricity system. In fact, the COVID-19 pandemic led to a significant decline in electricity consumption, a fuel switch in the merit order, and ultimately, to a higher overall share of renewables in Germany.

As for Germany, such an increase in intermittent renewables comes along with a growing need for flexibility measures to balance demand and variable electricity generation. During the COVID-19 pandemic, for Germany one key flexibility measure was the exchange of electricity via transmission lines within the interconnected European power network. In this paper, we therefore analyzed Germany's increase in electricity imports from a market, environmental, and network perspective. To the best of our knowledge, we are the first to present analyses and discuss on the question what we can learn from the development of German electricity imports as a flexibility option in an interconnected power network during the COVID-19 pandemic from those three perspectives.

Based on data from the ENTSO-E Transparency Platform on electricity imports and electricity exports (for both scheduled commercial exchange and physical power flows), Day-Ahead electricity prices, electricity generation for countries within the power network of the ENTSO-E, and interconnection capacities, we used data visualization and statistics to analyze what effects the altered electricity imports/exports of Germany during this period had on the interconnected European power network. We formulated three hypothesis that serve to partition our overarching research question.

Our work contributes to the understanding of the electricity import and export behavior of European countries with a focus on Germany during the COVID-19 pandemic. Thereby, we cannot confirm that as a result of Germany's increased need for transmission flexibility the prices for German electricity imports from neighboring bidding zones increased as well. Our results also reveal that while exhibiting an increased share of renewables Germany increasingly relied on electricity imports from the interconnected European power network. Furthermore, during the COVID-19 pandemic in 2020, electricity imports of Germany on average exhibited a lower share of renewables. Moreover, our results indicate that electricity imports of Germany in 2020 to a large part stemmed from nuclear power plants in France and Switzerland. Finally, our results reveal that during the COVID-19 pandemic the French, Dutch, and Swiss interconnection capacities to Germany experienced higher levels of utilization compared to previous years. Answering our research question, we can, in particular, learn three aspects from the development of German electricity imports as a flexibility option during the COVID-19 pandemic: First from a market perspective, Germany's increased need for electricity imports did not result in increased prices for all neighboring bidding zones. Second, from an environmental perspective during this time, Germany increasingly relied on electricity imports from countries that exhibited a lower share of renewables and thus made use of the diversity of the interconnected European power network by importing electricity from, e.g., Swiss and French nuclear power plants or Dutch gas electricity generation technologies. Finally, from a network perspective during the COVID-19 pandemic the interconnection capacities of Germany and France, the Netherlands and Switzerland exhibited high levels of utilization and thereby relied on the transmission lines of those regional networks within the interconnected European power network. From an international perspective, we contribute to research on interconnected power networks by investigating electricity imports in the interconnected European power network under altered circumstances during the COVID-19 pandemic. In this context, our results reveal that during the COVID-19 pandemic Germany increasingly relied on the advantages of such an interconnected network where Germany benefited from diversification of generation technologies and interconnection capacities which both allowed increased electricity imports.

Even though we present important insights into the European imports/exports behavior during COVID-19, however, our work also exhibits some limitations. Our analyses focus on electricity imports of Germany from its neighboring countries, examining the (foreign) electricity generation mixes, prices, and interconnection capacities. However, to gain a comprehensive understanding of the relationships prevailing during COVID-19, it might be necessary to also look at electricity consumption of the neighboring countries in more detail. In addition, it might be worthwhile to deepen the analyses on the individual characteristics of the generation technologies with a focus on whether it is dispatchable or non-dispatchable. Such investigation might provide further insights into the extent to which the intermittency of renewables may become a challenge in an interconnected power network. Intermittent renewables often also exhibit seasonal patterns. In this context our analyses regarding the relationship between the share of renewables and the amount of electricity imports (considering the time slot) can serve as a starting point. However, further research should deepen these analyses and tackle the question of how an increasing share of intermittent renewables might influence the time patterns of electricity imports during course of the year, week, and day. In light of our hypothesis H2, it might also be meaningful to examine the corresponding carbon footprint of Germany's electricity imports during the COVID-19 pandemic. Thereby, further research can base on our analyses of the share of RES in the electricity generation mixes of exporting countries. Regarding loop flows, our analyses include data on commercial as well as on physical imports and exports. However, in our analyses we only compare both import/export categories and do not explicitly identify or eliminate loop flows. Therefore, it would be worthwhile to perform additional quantitative analyses on the deviations between commercial and physical imports/exports. Finally, with regard to the increasing relevance of interconnected power networks worldwide, further research might compare the effects of the COVID-19 pandemic on different interconnected power networks such as the Eastern Interconnection in North America and analyze similarities as well as differences.

During the COVID-19 pandemic, the interconnected European power network was subject to unique circumstances. This crisis temporarily led to border closures which also had various effects on the electricity sector. Here, Germany made (an increased) use of international transmission lines which allowed an increasing share of renewables within the German electricity generation mix. Germany, in particular, relied on electricity imports from conventional power plants of its neighboring countries leading to a higher utilization of the corresponding interconnection capacities. Such insights emphasize the importance of a joint, coordinated interconnected European power network and sufficient flexibility options to cope with an increasing share of intermittent renewables. Overall, European policies should directly consider effects of the interconnected European power network, also with regard to climate targets. Therefore, a strong coordination of national strategies to jointly tackle the challenges arising from the climate crisis is highly important for the future European electricity system.

Credit author statement

Halbrügge, Stephanie: Conceptualization, Investigation, Writing – original draft, Data Formal analysis, Visualization. Buhl, Prof. Hans Ulrich: Conceptualization, Writing – Editing, Supervision. Fridgen, Prof. Gilbert: Conceptualization, Writing – Editing, Supervision, Schott, Dr. Paul: Conceptualization, Investigation, Writing – original draft, Data Formal analysis, Visualization. Weibelzahl, Dr. Martin: Conceptualization, Investigation, Writing – original draft, Editing. Weissflog, Jan: Conceptualization, Investigation, Writing – original draft, Data Formal analysis, Visualization.

Declaration of competing interest

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

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Appendix

Table 6
List of abbreviations for the 38 European bidding zones

Abbreviation	Country	Abbreviation	Country
AL	Albania	IT	Italy
AT	Austria	LT	Lithuania
BA	Bosnia and Herzegovina	LV	Latvia
BE	Belgium	MD	Moldova
BG	Bulgaria	ME	Montenegro
BY	Belarus	MK	Macedonia
CH	Switzerland	MT	Malta
CZ	Czech Republic	NL	Netherlands
DE-(AT)-LU	Germany-(Austria)-Luxembourg	NO2	Norway
DK1 + DK2	Denmark	PL	Poland
EE	Estonia	PT	Portugal
ES	Spain	RO	Romania
FI	Finland	RS	Serbia
FR	France	RU	Russia
GB	Great Britain	SE4	Sweden
GR	Greece	SI	Slovenia
HR	Croatia	SK	Slovakia
HU	Hungary	TR	Turkey
IE - SEM	Ireland	UA	Ukraine

References

[1] Net public electricity generation in Germany in 2020, Tech. rep. Fraunhofer Institute for Solar Energy Systems ISE; 2021.
[2] Liu S, Yang Z, Xia Q, Lin W, Shi L, Zeng D. Power trading region considering long-term contract for interconnected power networks. Appl Energy 2020;261:114411.
[3] Prol JL, Sungmin O. Impact of covid-19 measures on short-term electricity consumption in the most affected eu countries and USA states. iScience 2020;23(10):101639.
[4] Jiang P, Van Fan Y, Klemeš JJ. Impacts of covid-19 on energy demand and consumption: challenges, lessons and emerging opportunities. Applied Energy; 2021. p. 116441.
[5] Elavarasan RM, Shafiullah G, Raju K, Mudgal V, Arif M, Jamal T, et al. Covid-19: impact analysis and recommendations for power sector operation. Appl Energy 2020;279:115739.
[6] Halbrügge S, Schott P, Weibelzahl M, Buhl HU, Fridgen G, Schöpf M. How did the German and other european electricity systems react to the covid-19 pandemic? Appl Energy 2021;285:116370.

[7] Chiaramonti D, Maniatis K. Security of supply, strategic storage and covid19: which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport? Appl Energy 2020;271:115216.
[8] Werth A, Gravino P, Prevedello G. Impact analysis of covid-19 responses on energy grid dynamics in europe. Appl Energy 2020;281:116045.
[9] Heffron R, Körner M-F, Schöpf M, Wagner J, Weibelzahl M. The role of flexibility in the light of the covid-19 pandemic and beyond : contributing to a sustainable and resilient energy future in europe, Renewable & Sustainable Energy Reviews. URL, https://eref.uni-bayreuth.de/62070/.
[10] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807.
[11] Bichler M, Buhl HU, Knörr J, Maldonado F, Schott P, Waldherr S, et al. Electricity Markets in a Time of Change: A Call to Arms for Business Research. Schmalenbach J Bus Res 2022:1–26. https://doi.org/10.1007/s41471-021-00126-4.
[12] Papaefthymiou G, Haesen E, Sach T. Power system flexibility tracker: indicators to track flexibility progress towards high-res systems. Renew Energy 2018;127:1026–35.
[13] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80.
[14] Müller T, Möst D. Demand response potential: available when needed? Energy Pol 2018;115:181–98.
[15] Böckers V, Haucap J, Heimeshoff U. Cost of non-Europe in the single market for energy: annex IV: benefits of an integrated European electricity market: the role of competition. Publications Office of the European Union; 2013.
[16] Morshed MJ, Fekih A. A new fault ride-through control for dfig-based wind energy systems. Elec Power Syst Res 2017;146:258–69.
[17] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable european energy system. Energy 2018;160:720–39.
[18] ENTSO-E. System separation in the continental europe synchronous area on 8 january 2021 – 2nd update. https://www.entsoe.eu/news/2021/01/26/system-separation-in-the-continental-europe-synchronous-area-on-8-january-2021-2nd-update/.
[19] Osorio S, Pietzcker RC, Pahle M, Edenhofer O. How to deal with the risks of phasing out coal in Germany. Energy Econ 2020;87:104730.
[20] Steffen B, Egli F, Pahle M, Schmidt TS. Navigating the clean energy transition in the covid-19 crisis. Joule 2020;4(6):1137–41.
[21] Hosseini SE. An outlook on the global development of renewable and sustainable energy at the time of covid-19. Energy Res Social Sci 2020;68:101633.
[22] Alvarez GE. A multi-objective formulation of improving flexibility in the operation of electric power systems: application to mitigation measures during the coronavirus pandemic. Energy 2021;227:120471.
[23] Klemeš JJ, Van Fan Y, Jiang P. The energy and environmental footprints of covid-19 fighting measures–ppe, disinfection, supply chains. Energy 2020;211:118701.
[24] Brosemer K, Schelly C, Gagnon V, Arola KL, Pearce JM, Bessette D, Olabisi LS. The energy crises revealed by covid: intersections of indigeneity, inequity, and health. Energy Res Social Sci 2020;68:101661.
[25] Zhang X, Pellegrino F, Shen J, Copertaro B, Huang P, Saini PK, Lovati M. A preliminary simulation study about the impact of covid-19 crisis on energy demand of a building mix at a district in Sweden. Appl Energy 2020;280:115954.
[26] Nižetić S. Impact of coronavirus (covid-19) pandemic on air transport mobility, energy, and environment: a case study. Int J Energy Res 2020;44(13):10953–61.
[27] Abu-Rayash A, Dincer I. Analysis of mobility trends during the covid-19 coronavirus pandemic: exploring the impacts on global aviation and travel in selected cities. Energy Res Social Sci 2020;68:101693.
[28] Bazzana D, Cohen JJ, Golinucci N, Hafner M, Noussan M, Reichl J, Rocco MV, Sciullo A, Vergalli S. A multi-disciplinary approach to estimate the medium-term impact of covid-19 on transport and energy: a case study for Italy. Energy; 2021. p. 122015.
[29] 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(3):489–95.
[30] Hilares K, Vargas R, Gastelo-Roque JA. Impact of covid-19 on the ghg emissions of the peruvian interconnected electrical system. In: 2020 IEEE XXVII international conference on electronics, electrical engineering and computing (INTERCON). IEEE; 2020. p. 1–4.
[31] Bahmanyar A, Estebsari A, Ernst D. The impact of different covid-19 containment measures on electricity consumption in europe. Energy Res Social Sci 2020;68:101683.
[32] 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 Pol 2021;148:111964.
[33] Liu X, Lin Z. Impact of covid-19 pandemic on electricity demand in the UK based on multivariate time series forecasting with bidirectional long short term memory. Energy 2021;227:120455.
[34] Krarti M, Aldubyan M. Review analysis of covid-19 impact on electricity demand for residential buildings. Renewable and Sustainable Energy Reviews; 2021. p. 110888.
[35] Abu-Rayash A, Dincer I. Analysis of the electricity demand trends amidst the covid-19 coronavirus pandemic. Energy Res Social Sci 2020;68:101682.
[36] Lu H, Ma X, Ma M. A hybrid multi-objective optimizer-based model for daily electricity demand prediction considering covid-19. Energy 2021;219:119568.
[37] Heffron RJ, Körner M-F, Schöpf M, Wagner J, Weibelzahl M. The role of flexibility in the light of the covid-19 pandemic and beyond: contributing to a sustainable and resilient energy future in europe. Renew Sustain Energy Rev 2021;140:110743.
[38] Sikarwar VS, Reichert A, Jeremias M, Manovic V. Covid-19 pandemic and global carbon dioxide emissions: a first assessment. Sci Total Environ 2021;794:148770.
[39] Han P, Cai Q, Oda T, Zeng N, Shan Y, Lin X, Liu D. Assessing the recent impact of covid-19 on carbon emissions from China using domestic economic data. Sci Total Environ 2021;750:141688.
[40] Le Quéré C, Jackson RB, Jones MW, Smith AJ, Abernethy S, Andrew RM, et al. Temporary reduction in daily global co 2 emissions during the covid-19 forced confinement. Nat Clim Change 2020:1–7.
[41] Zhang J, Cheng C, Yu S, Wu H, Gao M. Sharing hydropower flexibility in interconnected power systems: a case study for the China southern power grid. Appl Energy 2021;288:116645.
[42] Neumayer S, Modiano E. Assessing the effect of geographically correlated failures on interconnected power-communication networks. In: 2013 IEEE international conference on smart grid communications (SmartGridComm). IEEE; 2013. p. 366–71.
[43] Wu J, Wang P. Post-disruption performance recovery to enhance resilience of interconnected network systems. Sustain Resil Infrastruct 2021;6(1–2):107–23.
[44] Senthilkumar V, Reddy K, Subramaniam U. Covid-19: impact analysis and recommendations for power and energy sector operation. Appl Energy 2020;279:115739.
[45] ENTSO-E, Sftp guide. URL https://transparency.entsoe.eu/content/staticcontent/Static%20content/knowledge%20base/SFTP-TransparencyDocs.html.
[46] Hirth L, Mühlenpfordt J, Bulkeley M. The entso-e transparency platform–a review of europe's most ambitious electricity data platform. Appl Energy 2018;225:1054–67.
[47] Liu Z, Ciais P, Deng Z, Lei R, Davis SJ, Feng S, Zheng B, Cui D, Dou X, Zhu B, et al. Near-real-time monitoring of global co 2 emissions reveals the effects of the covid-19 pandemic. Nat Commun 2020;11(1):1–12.
[48] Haas R, Resch G, Panzer C, Busch S, Ragwitz M, Held A. Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources–lessons from eu countries. Energy 2011;36(4):2186–93.
[49] ENTSO-E. Welcome to the entso-e website. https://www.entsoe.eu/.
[50] Liu Z, Zhang Y, Wang Y, Wei N, Gu C. Development of the interconnected power grid in europe and suggestions for the energy internet in China. Glob Energy Interconnect 2020;3(2):111–9.
[51] ENTSO-E. Scheduled commercial exchanges. https://transparency.entsoe.eu/transmission-domain/r2/scheduledCommercialExchangesDayAhead/show.
[52] COMMISSION E. Communication from the commission - covid-19: temporary restriction on non-essential travel to the eu. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0115.
[53] ENTSO-E. Actual generation per production type. https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show.
[54] ENTSO-E. Cross-border physical flow. https://transparency.entsoe.eu/transmission-domain/physicalFlow/show.