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## Patterns and correlations in European electricity prices

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Julius Trebbien  ; Anton Tausendfreund  ; Leonardo Rydin Gorjão  ; Dirk Witthaut  



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Julius Trebbien,<sup>1,2</sup>  Anton Tausendfreund,<sup>1,2</sup>  Leonardo Rydin Gorjão,<sup>3</sup>  and Dirk Witthaut<sup>1,2,a)</sup> 

## AFFILIATIONS

<sup>1</sup>Institute for Energy and Climate Research—Energy Systems Engineering (IEK-10), Forschungszentrum Jülich, 52428 Jülich, Germany

<sup>2</sup>Institute for Theoretical Physics, University of Cologne, 50937 Köln, Germany

<sup>3</sup>Faculty of Science and Technology, Norwegian University of Life Sciences, 1432 Ås, Norway

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**a)** Author to whom correspondence should be addressed: [d.witthaut@fz-juelich.de](mailto:d.witthaut@fz-juelich.de)

## ABSTRACT

Electricity markets are central to the coordination of power generation and demand. The European power system is divided into several bidding zones, each having an individual electricity market price. While individual price time series have been intensively studied in recent years, spatiotemporal aspects have received little attention. This article provides a comprehensive data-centric analysis of the patterns and correlations of the European day-ahead electricity prices between 2019 and 2023, characteristically abnormal due to the energy crisis in Europe. We identify the dominant communities of bidding zones and show that spatial differences can be described with very few principal components. Most bidding zones in Continental Europe were brought together during the energy crisis: Correlations increased, and the number of relevant principal components decreased. Opposite effects occur in the Nordic countries and the Iberian Peninsula where correlations decrease and communities fragment.

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The European energy crisis, inextricably connected with the Russian invasion of Ukraine, resulted in electricity price levels never before seen. Europe's dependence on Russian gas led to soaring prices coupled with the uncertainty brought about by the war. Remarkably, the various electricity markets of each European country were affected in quite different, sometimes unexpected ways. As a consequence, topics in energy markets and energy security took center stage in the political discussion. Electricity markets have always been a central topic in energy economics, but the interactions and interdependencies of markets received rather little attention. This article provides a data-centric investigation of electricity prices in the various bidding zones in Europe and quantifies similarities and differences.

## I. INTRODUCTION

A reliable supply of electric power is crucial for almost all aspects of our daily lives. Most economic activities as well as most

technical infrastructures are dependent on the robust and stable operation of the electric power system, making it a uniquely critical infrastructure.<sup>1</sup> Since a power grid cannot easily store energy in itself, generation and demand must be balanced at all times.<sup>2</sup> A balanced system operates at a nominal frequency (commonly 50 or 60 Hz). Small deviations are corrected by the load-frequency control system in real time,<sup>3,4</sup> but most of the generation must be scheduled beforehand in order to match the forecasted demand of all consumers in the synchronous grid. In liberalized electricity markets, this is achieved by trading on various electricity markets,<sup>5</sup> wherein electricity producers and consumers buy and sell generation capacity. Apart from long-term contracts, the day-ahead spot markets play a central role in fulfilling the power demands of the consumers in the synchronous grid.<sup>6,7</sup>

The aggregation of generation and demand in an interconnected synchronous grid can improve the stability and efficiency of the grid for several reasons. First, long-distance transmission facilitates the balancing of variable renewable power sources.<sup>8</sup> Second, short-term power fluctuations average out, reducing the demand for

real-time control and improving frequency stability.<sup>9,10</sup> Finally, the liberalization and integration of markets increases competition and, thus, leads to lower costs.<sup>5</sup> For example, the Continental European (CE) synchronous area included a generation capacity of more than 600 GW and served more than 400 million customers as of 2021.<sup>11</sup>

Electricity trading in interconnected grids is limited by physical constraints. An overhead line can transmit only a certain amount of electric power before stability is at risk.<sup>2,12</sup> To reflect these limitations—and to create a financial incentive to supply power across countries—the European power system is divided into various bidding zones, often corresponding to the respective countries. Every bidding zone has its distinct electricity prices, reflecting the local supply and demand.

Electricity spot market prices across all European bidding zones have intricate statistical properties, featuring heavy tails and a strong persistence.<sup>6</sup> The complexity of the data reflects the inherent complexities of each bidding zone. These comprise the balance of renewable and non-renewable generation, the limitation of importing or exporting electricity, and naturally the daily human activity patterns. One element that highly influences the prices is the ability to sell or buy generation between adjacent bidding zones, be it between countries or even within a country.

In this article, we provide a statistical analysis of the *spatiotemporal properties* of electricity price time series in Europe between 2019 and 2023 and the impacts of the European energy crisis. Prices are coupled due to cross-border trading and common drivers, i.e., similar temporal patterns of the demand. This gives rise to strong correlations and intricate spatiotemporal patterns reflecting the specific power demands of each bidding zone. Moreover, the energy markets are inextricably coupled to the gas and oil markets in Europe. Price changes in these, driven by either market economics or political events, inadvertently affect electricity prices.<sup>13</sup> In fact, the European energy crisis related to the Russian invasion of Ukraine strongly affected the electricity systems across Europe,<sup>13,14</sup> but impacts differed from country to country. Hence, we observe not just an overall increase in electricity prices but a comprehensive modification of their correlations and spatiotemporal patterns.

The article is structured as follows. We provide a short review of the structure and functioning of European electricity markets in Sec. II. We then give an overview of the price time series and their fundamental statistical properties in Sec. III, including a first glimpse on the effect of the European energy crisis. Section IV contains a detailed analysis of the spatial correlations of the electricity price time series. We then proceed to identify and investigate the main spatiotemporal patterns of day-ahead electricity prices in Sec. V. We conclude with a short discussion and outlook in Sec. VI.

## II. BACKGROUND: ELECTRICITY MARKETS AND PRICES

### A. European electricity markets

In liberalized electricity markets, the balancing of power systems is mainly achieved by trading of generation and consumption capacities. Each market participant must sell or buy the electricity that they are going to inject or withdraw from the grid in a certain time window.<sup>15</sup> For instance, an operator of a photovoltaic power

plant, upon agreeing on a forward contract on the electricity spot market, must deliver the exact amount of electricity that they sold in any given hourly time window.

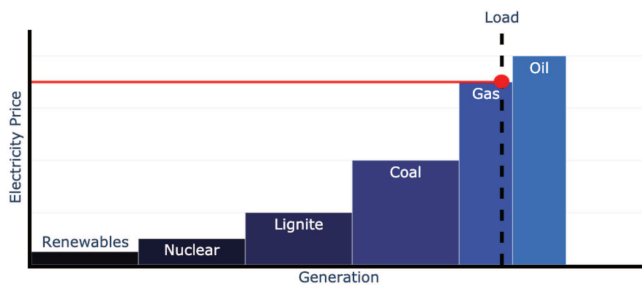
Market participants may buy and sell electricity either via individual long-term contracts, commonly referred to as power purchase agreements (PPAs), via over-the-counter (OTC) direct contracts, or via trading on an electricity exchange. Given the variability in generation and consumption due to different factors, such as changing weather, most market participants are dependent on forecasts.<sup>16</sup> Since forecasts become increasingly uncertain as the time horizon extends from actual delivery, a variety of electricity markets including future, day-ahead, and intraday markets exist within Europe. The spot markets are the main market for physical trading of electricity and consist of the day-ahead and intraday markets.<sup>7,17,18</sup> The European day-ahead markets generally trade in hourly blocks for the 24 hours of the following day and close at 12:00 CET. Different exchanges may adopt slightly different rules but mostly follow the mentioned structure.<sup>19</sup>

Day-ahead trading is auction-based, i.e., the bids and offers of all market participants are collected inside the order book until market closure. Aggregating both offers and bids in volume for each hour creates the respective supply and demand curves. The Market Clearing Price (MCP) of the day-ahead market results from the intersection between the supply and demand curve, which corresponds to the highest price that finds a buyer.<sup>20,21</sup> All bids and offers that are consistent with the price are realized at the market clearing price in the respective hour. Consequently, every offer below the market price and every bid above the market price gets executed exactly at the MCP, commonly referred to as “pay-as-cleared.” All bids below and all offers above the market clearing price are discarded.

The European electricity market is separated into bidding zones to reflect regional market conditions and limited transmission capacities. In principle, each bidding zone constitutes a separate electricity market with a separate market clearing price. Clearing the bidding zones individually ensures that generation and load are balanced regionally, given the limited capacities for long-distance transmission. Bidding zones are coupled to a limited extent as described below to enable exports and imports. In Europe, most bidding zones correspond to countries, with some countries sharing a bidding zone or being divided into several inter-country bidding zones.<sup>22</sup> For instance, Norway, Sweden, and Italy are divided into various smaller bidding zones within each country.

For the 12:00 day-ahead auction, the different bidding zones are coupled through the Single Day-Ahead Coupling (SDAC) mechanism. The SDAC, implemented in northwest Europe in 2014 and later expanded to most European bidding zones, integrates day-ahead electricity markets across Europe. The mechanism enhances market efficiency by pooling demand and supply across bidding zones, breaking the confines of local markets with respect to transmission capacity constraints between bidding zones.<sup>23</sup>

The aim of market coupling is to increase the efficiency of trading through increased liquidity and efficient utilization of all generation resources in Europe.<sup>24</sup> In contrast, transmission capacities within a bidding zone are not resolved and must be dealt with afterward.<sup>12</sup>



**FIG. 1.** Visualization of the merit-order principle. Generation is sorted according to their estimated marginal cost. The load is approximated as independent of the price. The price is set by the power plant with the highest marginal cost needed to match the load. Typically, renewable generation has the lowest marginal cost such that it is always included in the merit-order principle. Therefore, power plants using fossil fuels, such as coal, gas, or oil power plants determine the price.

The SDAC employs the *PCR EUPHEMIA* algorithm for price calculation and capacity allocation, completing these tasks for all zones and hourly intervals of the next day.<sup>25</sup> *EUPHEMIA* processes inputs from Nominated Electricity Market Operators (NEMOs) and Transmission System Operators (TSOs), encompassing order books and network constraints (e.g., interconnector restrictions, line losses, tariffs). The optimization algorithm maximizes social welfare by considering consumer and supplier surplus alongside congestion rent.<sup>26</sup>

We note that the actual generation may differ from the amount that has been sold on an electricity market, for instance, due to forecasting errors. Various layers of control reserve are implemented to balance the generation in real-time but are limited to small imbalances.<sup>3</sup> Most countries or bidding zones have energy reserve markets to promote balancing schemes for small power imbalances, but this is beyond the scope of the present article.

## B. The merit-order principle

The temporal evolution of the electricity market price  $p(t)$  in one bidding zone can roughly be understood from the merit-order principle.<sup>27</sup> In the short run, the demand for electricity  $D$  is largely inelastic.<sup>28</sup> In perfect competition, the demand is satisfied by generating units according to their marginal costs. All units with marginal costs below the market price  $p$  can realize positive contribution margins and are, thus, “on,” all others are “off.” Hence, one can obtain an approximate view of the market outcome by sorting all generating units according to their estimated marginal costs—the merit order. The marginal cost of the last power plant entering the market then corresponds to the market clearing price as illustrated in Fig. 1.

The merit-order principle can be formalized as follows. At each point in time, the demand must equal the sum of intermittent renewable generation (wind and solar) and dispatchable generation such that

$$G_{\text{ren}}(t) + G_d(p) = D(t). \quad (1)$$

Here,  $G_d(p)$  is the supply curve of the dispatchable generation according to the merit-order principle.<sup>27</sup> Renewable generation and demand are assumed to be independent of the market price  $p$  but

vary strongly in time. Solving Eq. (1) for the market price, thus, yields

$$p(t) \approx G_d^{-1}[D(t) - G_{\text{ren}}(t)], \quad (2)$$

where  $G_d^{-1}$  denotes the inverse function of the supply curve. Hence, wind and solar generation and demand are essential factors that determine the electricity market price.<sup>29</sup>

We emphasize that Eq. (2) provides only a rough estimate of the actual market price as it neglects many other influencing factors.<sup>29</sup> Conventional power plants, especially nuclear and lignite plants, have limited flexibility such that any ramping or cycling induces additional costs.<sup>30</sup> Thus, in the short run, power plant operators may choose a bidding price below their marginal costs. In the case of a decreasing demand, the operators may bid at a lower price to remain in the market. In the medium to long run, fuel prices evolve and the set of dispatchable power plants changes, which also affects the function  $G_d(p)$ .

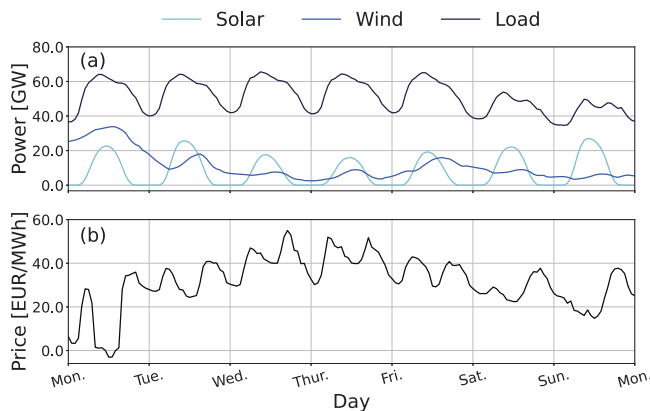
## III. ELECTRICITY PRICES AND THE EUROPEAN ENERGY CRISIS

In this section, we provide an overview of the spot market prices across Europe and the impact of European electricity prices. Our analysis is based on data from the European Network of Transmission System Operators for Electricity (ENTSO-E).<sup>31</sup> Further details are given in the Appendix.

### A. Electricity price time series

Before turning to spatiotemporal aspects, we review the essential aspects of price time series, focusing on a single bidding zone. Figure 2 shows the electricity price in the DE-LU bidding zone together with the load and renewable generation for one week. This figure highlights the main driving factors of electricity spot market prices as introduced in Sec. II B as well as typical recurring patterns. The load has a pronounced daily and weekly pattern, being substantially smaller during the night and on the weekend. The load typically peaks in the early morning and the evening, and so do the electricity prices. Solar power generation peaks at noon such that the residual load  $D(t) - G_{\text{ren}}(t)$  and the price  $p(t)$  assume a minimum. During the week displayed in the figure, wind power is decreasing such that we observe an overall increase in the electricity prices until the weekend. The relation of electricity prices and the residual load for European bidding zones has been investigated in Ref. 32 while further influences have been discussed in Ref. 29. Electricity price time series have intricate statistical properties including heavy tails and a pronounced persistence as discussed in detail in Ref. 6.

The European electricity markets were strongly affected by the European energy crisis of 2021 and 2022. Energy prices soared in many regions in connection to the Russian invasion of Ukraine.<sup>14</sup> Europe was particularly strongly affected due to the dependence on Russian fossil fuels in many countries. Figure 3 shows the electricity prices in the DE-LU bidding zone over a time period of several years. We observe a strong increase in the electricity prices starting at the end of 2021. While prices never exceeded 300 EUR/MWh before the crisis, they regularly do during the crisis with peaks above 800 EUR/MWh. Figure 3 also shows that it is generally not possible to pinpoint the exact start of the European energy crisis.



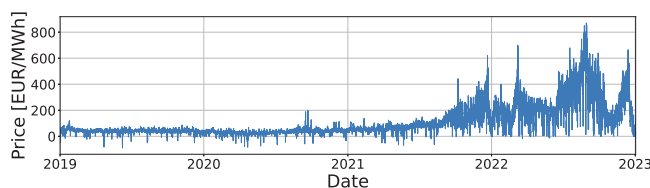
**FIG. 2.** Electricity prices and major driving factors. We show the time series for (a) load, solar power, and wind power generation and (b) the day-ahead spot market price in the DE-LU bidding zone for the week starting on 6 July 2020. Prices generally increase with the residual load, i.e., the load minus the variable renewable generation, cf. Sec. II B. Data sources and processing are summarized in the Appendix.

However, to be able to compare the data for the period before and during the energy crisis, we have set the start of the crisis to 13 September 2021, the first week in which the weekly average price in Europe was significantly higher ( $\geq 50$  EUR/MWh) than the average price of the previous six months. Further effects of the energy crisis have been discussed in the literature: The volatility of prices increased strongly,<sup>33</sup> and the likeliness of negative prices decreased drastically.<sup>34</sup>

## B. Differences between bidding zones

Electricity prices may differ considerably between the different bidding zones. In this section, we compare and discuss the global statistical features of respective price time series, before turning to the spatiotemporal correlations and patterns in the following.

Figure 4(a) shows the average day-ahead spot market price before the onset of the European electricity crisis. The lowest prices are observed in the Nordics, especially in the Northern bidding zones of Norway and Sweden, which is mostly due to the abundance of water power. The marginal costs of water power plants are typically very low such that electricity is offered at comparably low prices. At the same time, population density and, thus,



**FIG. 3.** Electricity price time series from the German day-ahead market from January 2019 to 2023. Data sources and processing are summarized in the Appendix.

load are rather small, resulting in low overall prices. The highest prices are observed in Italy, in particular, Sicily. Italy has a limited amount of generation facilities leading to a small supply and, thus, to higher prices. In fact, Italy imports a substantial amount of electricity from neighboring countries. For instance, in 2021, Italy imported a 46.6 TWh of electricity, while it exported only 3.8 TWh.<sup>35</sup>

The impact of the European electricity crisis is illustrated in Figs. 4(b) and 4(c). We observe that the average price increases strongly in many bidding zones up to a factor of almost six. Almost no change is observed in the Northern bidding zones of Norway and Sweden, which can again be attributed to the dominant role of water power, which was not affected by increasing fuel prices. Furthermore, the increase is rather modest in Finland, Southern Sweden, Poland, and the Iberian Peninsula. The electricity system in these bidding zones does not rely strongly on natural gas imports from Russia for different reasons. Power generation in Sweden and Finland mainly relies on nuclear power, while domestic coal and lignite are dominant in Poland. Spain and Portugal import almost no natural gas from Russia but rely on liquefied natural gas (LNG) from other sources instead.<sup>35</sup>

The strongest increase in prices is observed in Southern Norway and France. This is surprising because power generation in these bidding zones does *not* rely strongly on Russian natural gas—but on water power in Norway and nuclear power in France.<sup>35</sup>

These unexpected findings can be connected to two effects that occurred simultaneously but independently of the Russian invasion of Ukraine. First, a large number of French nuclear power plants had to go into revision. Figure 5(a) shows the reported unavailability of nuclear generation capacity. There is a strong seasonal pattern as revisions are preferably planned during the summer months. Comparing different years, we find that the unavailability reached previously unknown values of more than 36 GW during summer 2022. Similarly, the unavailability in the winter 2021/2022 was higher than in preceding winters by several GW. We conclude that the price increase in the French bidding zone can be attributed to at least partially to this effect.

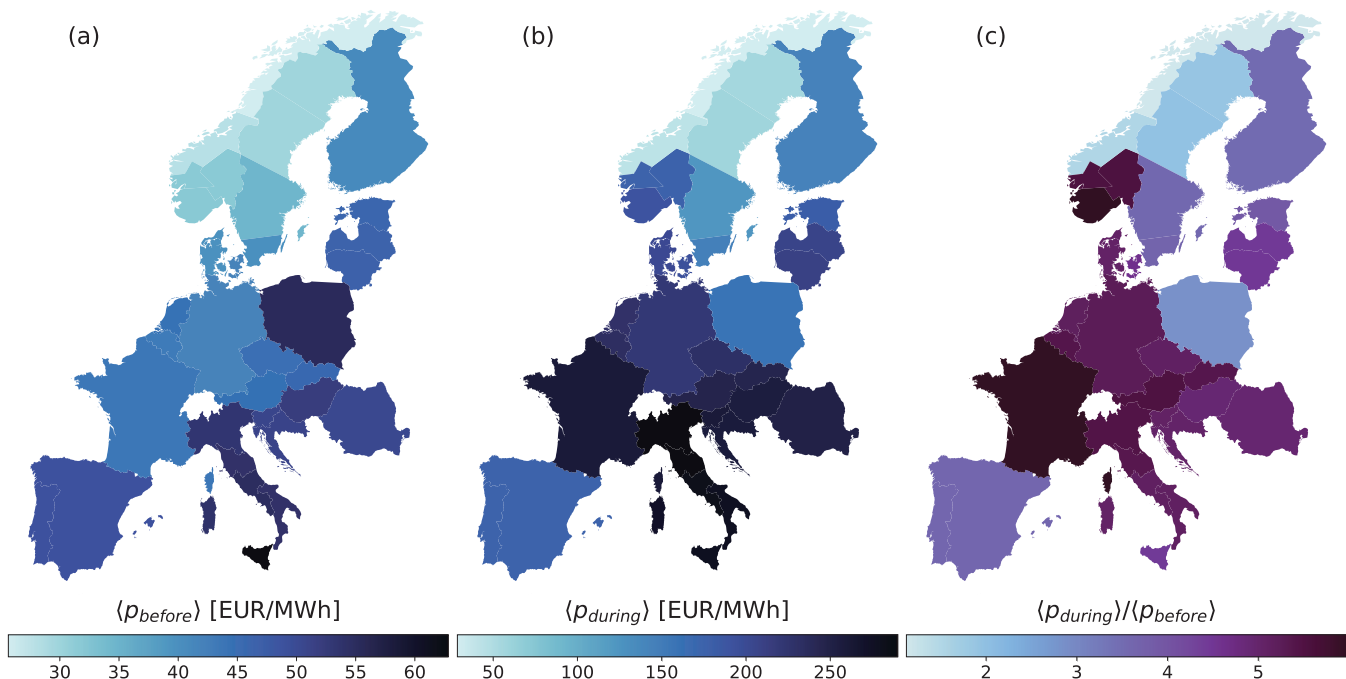
The strong increase in Southern Norway occurs at the time when the NordLink interconnection to Germany was put into commercial operation in 2021.<sup>36</sup> This high-voltage DC connection has a transmission capacity of 1.4 GW, the actual power exchange being shown in Fig. 5(b). NordLink enables direct electricity trading between the bidding zones in Germany (DE-LU) and Norway (NO2), which typically leads to an alignment of the respective day-ahead prices. Given the comparably small size of the NO2 bidding zone, we expect a much stronger effect than in the German bidding zone. Indeed, we see that the average price  $p_{\text{during}}$  shown in Fig. 4(b) is very similar.

## IV. CORRELATIONS AND COMMUNITIES

In this section, we turn to the spatiotemporal aspects of electricity prices in Europe. We first quantify correlations of price time series and identify communities in the European markets.

Correlations emerge via two different mechanisms: common driving factors and mutual interactions. Common driving factors affect both the demand and supply curves in the individual bidding zones. The demand shows pronounced daily and weekly patterns,





**FIG. 4.** Average electricity price and the impact of the European electricity crisis. (a) and (b) The colormap shows the average day-ahead spot market price for each bidding zone before and during the European electricity crisis. (c) The colormap shows the ratio of the average price during and before the crisis. In some bidding zones, the prices increase up to a factor of almost six. Data sources are summarized in the [Appendix](#).

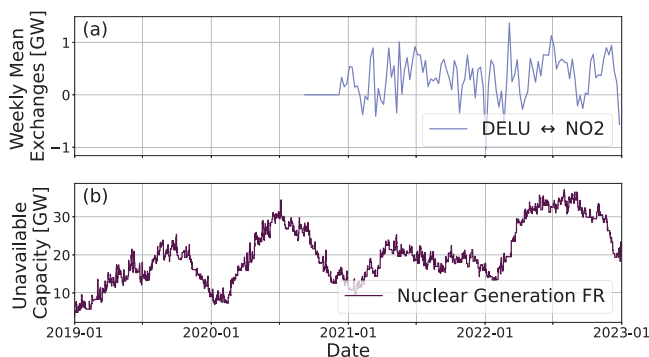
which are similar in most bidding zones.<sup>37,38</sup> The availability of renewable power also shows regular patterns, in particular, seasonal patterns<sup>39</sup> and daily patterns for solar power. Furthermore, the actual weather is strongly correlated on the synoptic scale of around

1000 km. As a consequence, electricity price time series in different bidding zones show similar recurring patterns and similar reactions to the weather, albeit at different magnitudes.

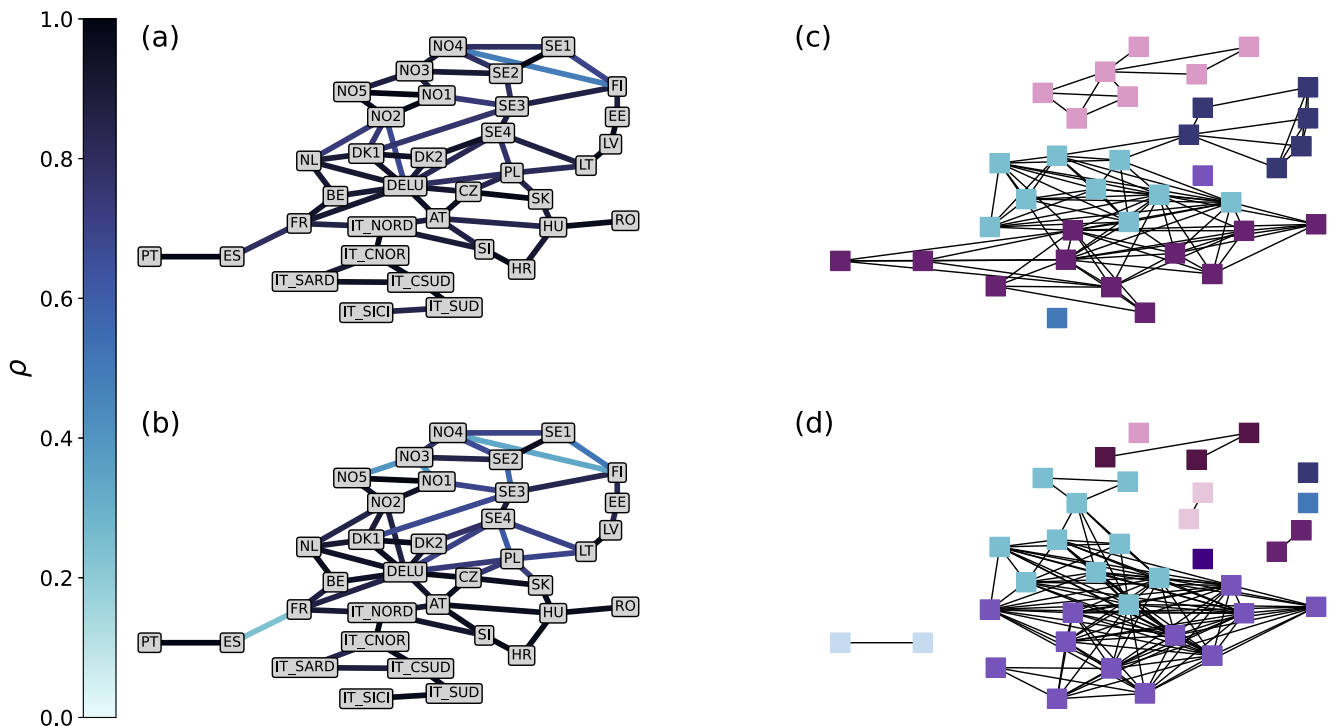
Cross-border electricity trading introduces an interaction between neighboring bidding zones. Consider the case that the price  $p_x$  in bidding zone  $x$  is lower than the price  $p_y$  in a neighboring bidding zone  $y$ . In general, the EUPHEMIA algorithm will select further offers in bidding zone  $x$  and discard offers in bidding zone  $y$  to reduce the overall prices. As a consequence, the price in zone  $x$  increase, and the price in zone  $y$  decreases. Loosely speaking, cross-border trading leads to an averaging of prices in neighboring bidding zones.

We quantify the emerging correlations in terms of the Pearson coefficient  $\rho_{x,y}$ , which is illustrated for all neighboring bidding zones in [Figs. 6\(a\)](#) and [6\(b\)](#). As before, we distinguish the periods *before* and *during* the European energy crisis. We observe a substantial decrease for some connections, in particular, Spain and France, Norway (NO3, NO4, and NO5), and Finland, and for several connections of Poland. Other correlations increase, for instance, NO2 and DE-LU. The last finding may be attributed, at least partially, to the operation of NordLink as discussed above.

Further insights into the spatial aspects are obtained in terms of correlation networks (cf. [Refs. 40 and 41](#)). Here, every bidding zone corresponds to a node of a network. Two bidding zones  $x$  and  $y$  are connected if the mutual Pearson correlation exceeds a threshold  $\rho_{x,y} > h$ . Note that we now take into account all pairs of bidding zones in accordance with the literature.<sup>40,41</sup> We note that in many



**FIG. 5.** Features affecting electricity supply and trading in 2021/2022. (a) The NordLink interconnector between Germany and Norway was put into commercial operation in 2021.<sup>36</sup> The figure shows the physical exchange between Norway (NO2) and Germany (DE-LU) as a function of time, averaged over one week. Positive values correspond to a flow from Norway to Germany. (b) The reported unavailability of nuclear power plants in France was larger than in previous years. Data sources are summarized in the [Appendix](#).



**FIG. 6.** Correlations and communities of the European electricity price time series. (a) and (b) Pearson correlation  $\rho$  between neighboring bidding zones (a) before and (b) during the energy crisis. (c) and (d) Correlation networks and communities. Two bidding zones  $x, y$  are linked if the mutual Pearson correlations exceed a threshold  $\rho_{x,y} > h = 0.85$ . Communities in these networks are marked by different colors. Communities are computed (c) before and (d) during the energy crisis. Data sources are summarized in the [Appendix](#).

applications, time-delayed correlations are used in the context of causal interactions. This is not appropriate in our case as all prices are set simultaneously.

The resulting correlation networks are shown in [Figs. 6\(c\)](#) and [6\(d\)](#) for the threshold parameter  $h = 0.85$ , comparing the period before and during the energy crisis. We observe two general effects: The number of edges decreases in the Nordics and the Baltics and for the Iberian Peninsula, while they increase in Continental Europe. We recall that correlations emerge due to two reasons: Common drivers and trading interactions. The observed changes in the number of links, thus, do not necessarily hint at less or more intense trading. Instead, it is also possible that the susceptibility to external drivers became less similar (the Nordics) or more similar (Continental Europe).

In a second step, we apply the Louvain algorithm<sup>42</sup> to identify communities in the respective network. For this, we use the implementation of the networkx python package with default parameters, i.e., resolution set to 1.<sup>43</sup>

Before the crisis, the correlation network can be decomposed into six communities. First, we observe a Western Scandinavian and a Baltic community that are not connected at all for the given value of  $h$ . Notably, the Swedish bidding zones belong to different communities. Several high-voltage DC links enable electricity trading across the Baltic Sea, most notably NordBalt between Sweden and

Lithuania and Estlink between Finland and Estonia.<sup>44</sup> We conclude that these links are essential for the formation of the Baltic community.

Continental Europe is divided into a Northern and a Southern community, the border roughly following the Alps and the Slovakian–Hungarian border. The community boundary may, thus, be at least partially explained in terms of the physical geography of Europe. According to [Fig. 4\(a\)](#), we observe that average prices are higher throughout the Southern community. Unsurprisingly, Poland and Sicily form their own community as their electricity markets differ considerably from their neighbors. Poland has a distinct fuel mix, relying strongly on domestic coal and lignite.<sup>35</sup>

The energy crisis has a stark effect on the correlation network in Northern Europe. The Nordic and Baltic communities fall apart into small fragments. This observation has to be interpreted in terms of the different fuel mix of each country and the dependency on Russian imports. On the one hand, Northern Norway and Northern Sweden rely strongly on water power such that prices were only weakly affected [cf. [Fig. 4\(c\)](#)]. On the other hand, the Baltic countries are still part of the Russian synchronous area<sup>45</sup> and prices were affected to a much higher extent [cf. [Fig. 4\(c\)](#)]. At the same time, the Southern Norwegian bidding zones join the Northern Continental community, which again may be attributed to the operation of the NordLink interconnector.

In Continental Europe, the number of edges generally increases during the energy crisis. A remarkable effect is observed for France, where correlations change considerably. These changes are not surprising given that France suffered a strong increase in nuclear unavailability [cf. Fig. 5(b)] and the strongest increase in average prices (cf. Fig. 4). In fact, one observes strong changes in the patterns of electricity trading between France and its neighbors. Comparing 2021 and 2022, France turned from a net exporter (43.4 TWh) to a net importer (16.5 TWh).<sup>46</sup> The only exception is trading with Italy, which remained largely constant.<sup>46</sup> This manifests in changes of price correlations, which generally decreased between France and Northern Europe but stayed high or even increased between France and Southern Europe. As a consequence, the French bidding zone left the Northern and joined the Southern community.

Finally, the correlation between Spain and France decreased strongly such that the Iberian Peninsula left the Southern Continental community. As discussed before, the Iberian Peninsula was only weakly affected by the European energy crisis as it barely imports natural gas from Russia.<sup>35</sup>

## V. ELECTRICITY PRICE PATTERNS

We now consider the spatiotemporal patterns of the European electricity price time series. We aim to identify and interpret the dominant patterns and discuss how they were affected during the energy crisis.

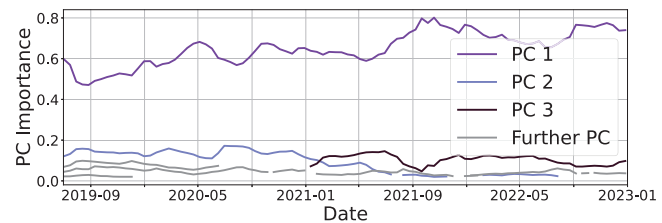
To this end, we aggregate all time series in a vector  $\vec{p}(t)$ , where the  $n$ th component corresponds to the electricity price time in a specific bidding zone  $n$  at time  $t$ . Our goal is to decompose this vector as

$$\vec{p}(t) = \langle \vec{p} \rangle + \sum_m a_m(t) \vec{c}_m, \quad (3)$$

such that  $\vec{c}_m$  describes a spatial pattern and  $a_m(t)$  the amplitude of the respective pattern at time  $t$ . The desired decomposition is provided by principal component analysis (PCA), a standard technique for dimensionality reduction.<sup>47</sup> This decomposition is optimal in the following way. PCA selects the vectors  $\vec{c}_m$ , called principal components (PCs), in a way that they capture as much of the variance of the original time series as possible. Technically, the PCs  $\vec{c}_m$  are given by the eigenvectors of the covariance matrix. The associated eigenvalue  $\lambda_m$  measures how much of the overall variance of the multivariate time series  $\vec{p}(t)$  is explained by the  $m$ th PC.<sup>47</sup> The ratio of  $\lambda_m$  and the total variance will serve as a measure of the importance of a PC in the following.

We remark that PCA is a *linear* method in the following sense. Restricting the sum in Eq. (3) to  $M$  PCs corresponds to a projection of the original data onto an  $M$ -dimensional *linear* subspace. PCA, thus, efficiently identifies all linear correlations but fails to account for nonlinear relations in the data. Advanced methods of nonlinear data reduction, thus, aim to replace the linear subspaces by low-dimensional manifolds of arbitrary shape.<sup>48</sup> In this initial analysis, we restrict ourselves to common linear PCA because of its high interpretability. Furthermore, we remark that the leading PC already covers up to 80% of the variance such that nonlinear effects can be assumed to be small.

In this context, we must take into account that electricity markets can change strongly over time as grids, regulations, or the fuel



**FIG. 7.** Importance of the principal components (PCs) for the price vector  $\vec{p}(t)$  as a function of reference time  $t_r$ . The PCs were computed for a sliding window of 180 days and tracked according to their overlap. The importance is quantified by the fraction of the total variance explained by a given PC. Only PCs with an explained variance of at least 5% are shown to increase visibility. PC1 refers to the most important PC, explaining up to 80% of the variance, and is further analyzed in Fig. 8. PC2 refers to the second most important PC at the beginning of the analysis, explaining up to almost 20% of the variance. PC2 decreases in importance and becomes less substantial during the energy crisis. PC3 refers to the second most important PC at the end of the analysis. Both PC2 and PC3 describe a north–south pattern as shown in Fig. 9.

markets evolve. Hence, we utilize an adaptive decomposition. We compute PCA for separate intervals  $[t_r - T, t_r]$  and then shift the reference date as  $t_r \rightarrow t'_r = t_r + \tau$ . In the following, we choose  $T = 180$  days and  $\tau = 14$  days. The individual PCs are then tracked to analyze their evolution. Two PCs  $\vec{c}_m$  and  $\vec{c}'_n$  at subsequent intervals are identified if their overlap exceeds a threshold,

$$|\langle \vec{c}'_n, \vec{c}_m \rangle| \geq 0.8. \quad (4)$$

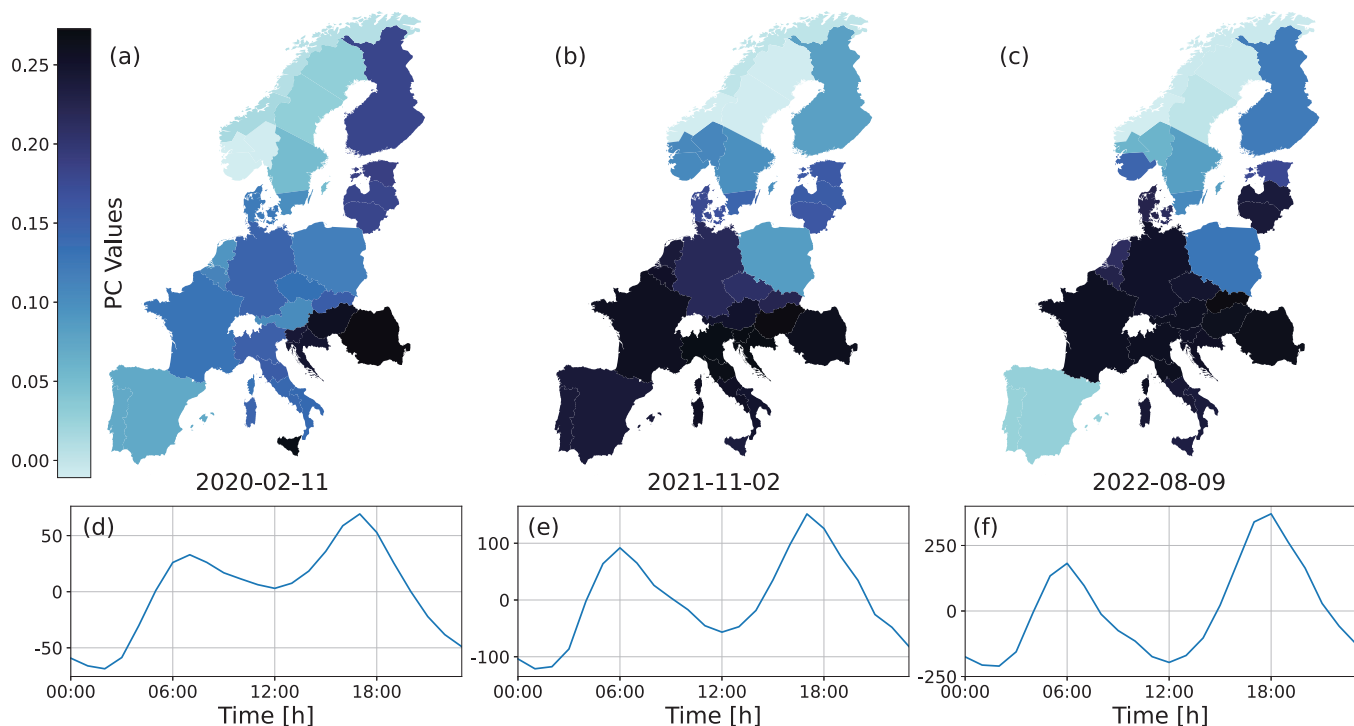
We have tested other values of the parameters  $T$  and  $\tau$  to assess the stability of the results. Choosing  $T$  substantially smaller than 180 days impedes the tracking of PCs and, thus, spoils interpretability. Choosing  $T = 365$  yields very similar results but reduces the temporal resolution of the analysis.

Figure 7 shows the variance explained by individual PCs as a function of time. We restrict the analysis to the most important PCs that explain at least 5% of the variance for a given interval  $[t_r - T, t_r]$ . Curves may stop or start if a PC cannot be tracked according to condition (4). We observe that only a few PCs are important to capture the spatiotemporal patterns of European electricity prices. The leading PC can be tracked over the entire time period and explains more than half of the variance for the vast majority of intervals  $[t_r - T, t_r]$ . The next-to-leading PC explains between 5% and 20% of the variance, but cannot be tracked over the entire period. In particular, we observe a change for a reference time  $t_r$  in early 2021. The importance of PC2 drops while another PC3 emerges and gains importance, replacing PC2 as the next-to-leading PC.

A detailed analysis of the most important PC and its temporal evolution is provided in Fig. 8. We display their spatial shapes  $\vec{c}_m$  at selected reference times  $t_r$ . Furthermore, we show their daily profile, i.e., the associated amplitude  $a_m(t)$  for all hours of the day, averaged over all days in the respective interval  $[t_r - T, t_r]$ .

We find that the leading PC1 mostly describes the response of the prices to the supply and demand illustrated in Fig. 2. The daily profile has a characteristic shape related to the daily profile of demand and solar generation. It peaks in the morning and





**FIG. 8.** The leading principal component PC1 of the price vector  $\vec{p}(t)$  and its temporal evolution. (a)–(c) The spatial pattern given by the components of the PC1 is shown as a colormap. (d)–(f) For further interpretation, we compute the daily profile of the PC. For all hours of the day, we average the amplitude  $a_1(t)$  over all days of the reference interval  $[t_r - T, t_r]$ . The PC is shown for three intervals: (a) and (d) before, (b) and (e) at the beginning and (c) and (f) during the energy crisis. The reference date  $t_r$  is given in the figure. This PC can be interpreted as the main response to changes in the residual load, leading to a characteristic daily pattern. The area of heavy participation in this pattern grows from the Balkan and Sicily before the crisis to most of Continental Europe during the crisis.

early evening and has its minimum during the night. The components of PC1 quantify how strongly the bidding zones participate in this temporal evolution. Before the energy crisis, bidding zones on the Balkan and Sicily show the strongest participation. The set of strongly participating countries extends during the energy crisis, covering most of Continental Europe. The participation is weak in the Nordics, the Iberian Peninsula, and, to a lesser degree, Poland and Estonia.

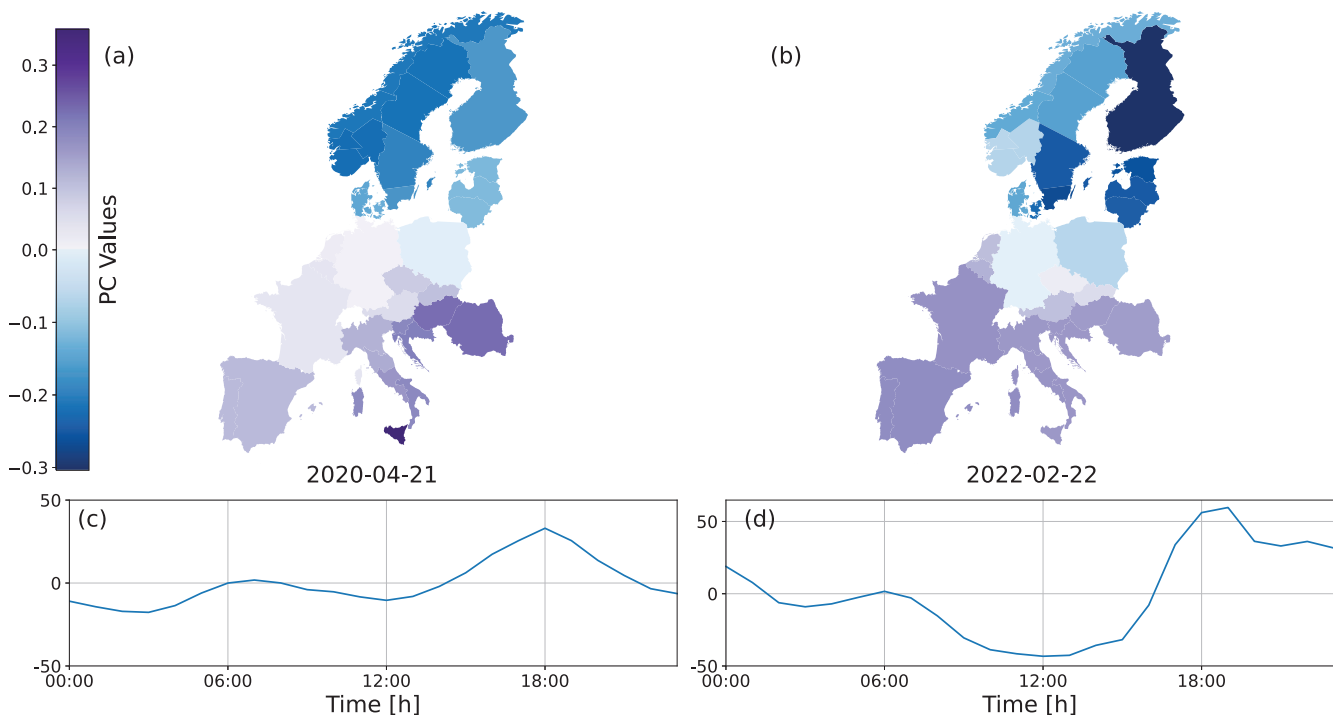
Notably, the Iberian Peninsula suffers a short period of participation in the early stage of the energy crisis and then reverts to levels from before the energy crisis [Fig. 8(c)]. This may be related to the independence of Portugal and Spain from Russian gas. In the emergence of the energy crisis, prior to the Russian invasion, prices in European bidding zones may be mainly driven by the uncertainty of a gas shortage in Europe. This results in the high volatility of the daily price patterns and, therefore, a strong participation of gas-dependent bidding zones. Once the actual impact of the energy crisis becomes evident, only the prices of countries with a high dependency on Russian gas stay highly volatile, reducing the participation of Portugal and Spain.

The observed spatial pattern largely coincides with the increase in the average prices during the energy crisis shown in Fig. 4(c). That

is, the energy crisis did not just lead to an overall increase in the price level in certain countries. Instead, prices in these countries became much more susceptible to changes in the residual load and, thus, more volatile (cf. Ref. 33). This effect was very similar in most of Continental Europe, boosting correlations and the importance of the respective PC.

The next-to-leading PCs are analyzed in Fig. 9. We observe that both PC2 and PC3 can be interpreted as north–south modes during the respective periods. Before the energy crisis, PC2 describes the price differences between the Nordics and Southern Europe, in particular, Sicily. We recall that average prices were higher in Southern Europe than in the Nordics, cf. Fig. 4. The analysis of the amplitude  $a_2(t)$  of PC2 shows that this trend is strongly amplified in the early evening, while it is attenuated at noon and during the night when either solar generation is high or demand is low.

During the energy crisis, we still observe a strong north–south mode given by PC3 but with different characteristics. Sicily no longer stands out, but France now shows a similar pattern as Southern Europe. On the other side, Finland now stands out on the opposite side. The amplitude now assumes its minimum at noon and remains positive most of the night.



**FIG. 9.** The next-to-leading principal components PC2 and PC3 of the price vector  $\vec{p}(t)$  for two intervals (a) and (c) before and (b) and (d) during the energy crisis. The reference dates  $t_r$  are given in the figure. We show (a) and (b) the spatial pattern given by the components of the PC  $\vec{c}_m$  and (c) and (d) the daily profile of the amplitudes  $a_m(t)$ . The second most important PC corresponds to a north–south mode, with Sicily being the driver before the energy crisis. During the energy crisis, the mode shifts to the Baltics.

## VI. CONCLUSION AND OUTLOOK

Electricity trading is essential for the coordination of generation and demand in liberalized electricity markets. The European electricity system is separated into several bidding zones that are coupled to enable cross-border electricity trading. In this work, we have conducted an analysis of European electricity price time series with a focus on the emerging correlations and spatiotemporal patterns.

Prices in different bidding zones are typically strongly correlated for two reasons. First, all markets are subject to similar driving factors including daily patterns of the demand or similar changes in the availability of renewable power. Second, cross-border trading typically induces an averaging effect such that prices in two neighboring bidding zones become more similar. The emerging correlations between bidding zones show distinct spatial patterns, which become most obvious in the associated correlation network. Before 2021, six regional communities could be observed in this network: Western Scandinavia, the Baltic Sea, Poland, Sicily, and two communities in Northern and Southern Continental Europe.

The European energy crisis starting in 2021 brought about significant changes both in the average electricity prices and in the spatiotemporal correlations and patterns, in particular, the community structure. While correlations in Continental Europe increased,

the communities in the Nordics fragmented. Stark changes were observed for France, Norway, and the Iberian Peninsula. The Southern Norwegian bidding zones became strongly coupled with the German–Luxembourg bidding zone and, thus, joined the Northern Continental community. France saw a strong increase in daily prices and turned from the Northern to the Southern European community, with increased correlations to Italy. In contrast, correlations to Spain diminished such that Portugal and Spain left the Southern Continental community.

While the European energy crisis is essentially connected to the Russian invasion of Ukraine and the soaring gas prices, not all observations can be linked to this reason. In particular, we conclude that the stark changes in Norway and France are strongly related to two simultaneous but independent events: The high unavailability of French nuclear power plants and the opening of the NordLink interconnector between Norway and Germany.

Typical spatiotemporal patterns were identified using principal component analysis in a sliding window. We have shown that regional differences in electricity prices can be largely described with just a very few important principal components. The most important principal component describes the different susceptibility of prices to changes in supply and demand. Some bidding zones are heavily affected and, thus, have a much higher variability of

prices and a stronger daily profile. The next-to-leading principle component describes a north–south mode.

Both principal components underwent substantial changes during the energy crisis. As the dependency on Russian gas imports, as well as other local factors, differs substantially between countries, so does the impact of the crisis. The leading principle component associated with the overall variability of prices changed its spatial shape during the crisis. The set of heavily affected countries grew from Italy and the Balkan to include large parts of Central Europe. Remarkably, Spain and Portugal were heavily affected only for a short period at the beginning of the crisis.

Our results shed light on the spatiotemporal interactions and dependencies of national electricity systems and markets. Cross-border trading is an important measure to balance the fluctuations of renewable power sources.<sup>8</sup> A strong development of cross-border interconnection capacities is foreseen in the next decade;<sup>49</sup> such that trading will become increasingly important.

Furthermore, our results may contribute to the growing field of electricity price forecasting.<sup>50</sup> Many current models focus on a single bidding zone. The observed strong correlations and patterns suggest that integrated modeling of all bidding zones is feasible and promising.

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## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

## Author Contributions

J.T. and A.T. contributed equally.

**Julius Trebbien:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Anton Tausendfreund:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Leonardo Rydin Gorjão:** Conceptualization (equal); Investigation (equal); Methodology (equal); Project administration (supporting); Supervision (supporting); Writing – original draft (equal); Writing – review & editing (equal). **Dirk Witthaut:** Conceptualization (equal); Investigation (equal); Methodology (equal); Project administration (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal).

## DATA AVAILABILITY

The raw data that support the findings of this study are openly available from the ENTSO-E Transparency Platform<sup>31</sup> and Eurostat.<sup>35</sup> Data processing is described in detail in the [Appendix](#).

## APPENDIX: DATA SOURCES AND PROCESSING

The raw data analyzed in this article are openly available. Time series of day-ahead load and renewable generation forecasts, day-ahead electricity prices and cross-border exchanges, and unavailable nuclear generation have been obtained from the ENTSO-E transparency platform.<sup>31</sup> Notably, the ENTSO-E transparency platform includes both planned and unplanned unavailabilities of power plants. We consider only the planned unavailabilities because contingencies occurring on short notice should not affect trading one on the day-ahead market. Data are retrieved via the ENTSO-E restful API using the open source python package `entsoe-py`.<sup>51</sup> Data on aggregated imports and exports and natural gas dependency on Russia are available at Eurostat.<sup>35</sup>

The raw data were processed at several points. Missing data for day-ahead forecasts of load, solar, and wind generation were replaced by actual load, solar, and wind generation. During a certain time period, the day-ahead prices for the bidding zones PL and RO were not denominated in EUR and were converted to EUR using a fixed exchange rate. The bidding zones of Italy changed on 1 January 2021. The region of Umbria was moved from IT-Centre-North to IT-Centre-South; the four production hubs IT-Brindisi, IT-Foggia, IT-Priolo, and IT-Rossano were eliminated; and IT-Calabria was added as a new bidding zone.<sup>52</sup> To account for this, data of the four hubs were aggregated with the bidding zone IT-South before 1 January 2021 and data from the bidding zones IT-Calabria and IT-South were aggregated after this date. Data of the bidding zones IT-Centre-North and IT-Centre-South remained unchanged.

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