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Electricity Markets Instability: Causes of Price Dispersion

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Abstract: The creation of a single competitive EU energy market is aimed at establishing a fair price in the integrated market space. However, electricity markets in European countries remain rather fragmented, and the marginal pricing method, which is the basic one used in the market, conditions a persistent price dispersion in the search for market equilibrium. This study examines the dispersion of electricity prices in 40 bidding zones in 26 European countries by means of quartile analysis. The geographic orientation of the markets, direction of electricity flows, and structure of electricity generation are considered as the causes of this dispersion. In the study, the geographical boundaries of the electricity markets are determined using the methods of correlation analysis of prices and transitive closure of commercial electricity flows. This makes it possible to single out highly integrated, moderately integrated, poorly integrated, and non-integrated markets. Using cluster analysis, electricity markets are classified according to the structure of electricity generation and direction of flows, with the identification of five clusters based on the dominant type of generation and three clusters based on the dominant direction of electricity supply. For each factor under investigation, the intragroup price dispersion is established. The results of the study have allowed to build a three-dimensional matrix that provides for determining the directions of changes in electricity prices when moving between its quadrants.

Keywords: electricity market; bidding zone; price dispersion; market conditions; generation structure; flow direction; geographical market boundaries

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1. Introduction

Electricity is a homogeneous product of a strictly regulated quality, which is ensured and maintained by the power grid. From a physical point of view, there cannot be any product differentiation [1,2]. This property determines the possibility of creating electricity markets close to the conditions of pure competition [3], including all the fundamental ones inherent in this form of competition: anonymity, homogeneity, perfect information, perfect mobility, unique market equilibrium configuration of quantity and price [4]. In practical terms, to fulfil these conditions in electricity markets, organized exchange platforms operated by market operators are created. They in turn provide the trading anonymity, automatic algorithm for matching bids and offers, and full awareness of participants about the trading results [5,6]. Today, these conditions are most inherent in the spot market (day-ahead and intraday markets) and partially the balancing electricity market, while forward markets are still dominated by imperfect forms of bilateral trade [7,8].

At the same time, from an economic point of view, electricity remains a heterogeneous product, differentiated over time and space by prices and delivery terms. Moreta, Papakonstantinoub (2020) believe that the heterogeneity of electricity is manifested in the fact that decision makers are affected by subjective attitudes towards uncertainties [9]. The heterogeneity of national electricity markets leads to constant price discrimination (both of demand and supply bids). Hughes and Lange note that the deregulation of electricity markets have improved their efficiency, and it also appears to have facilitated price discrimination, allowing suppliers to gain larger profits than they would have in a regulated market [10]. So, the economic heterogeneity of electricity, supported by price discrimination, leads to imperfect competition, i.e., instability in the electricity markets.

The liberalization of electricity markets, taking place all around the world, is aimed at establishing fair electricity prices and obtaining significant benefits for consumers under the pressure of competition. In theory, the need to deregulate electricity markets was proven by Bushnell and Wolak (1971) [11], and the feasibility of using marginal pricing in electricity markets was substantiated by Cicchetti, Gillen, Smolensky (1977) [12]. Practical steps to implement these ideas were made in the early 1990s.

The most intensively developing electricity markets are European ones. Over a 30-year period, they have moved from a vertically integrated monopolistic to a two-sided competitive model. The European model of electricity markets began to take shape in the mid-1990s. With the help of four energy packages (First was adopted in 1996, Second—in 2003, Third—2009, Fourth (called Clean Energy for all Europeans)—2018–2019), the EU is gradually opening up internal electricity markets to competition and strives to create a single transnational electricity market on the European continent [13,14]. The liberalization of European electricity markets has led to the unbundling of natural monopolies (transmission system operators and distribution system operators) and commercial participants (generators and suppliers). At the same time, the last ones can still remain affiliated with downstream and upstream providers, which may cause unfair distribution of forces in the market.

The current design of the European electricity market is based on a decentralized approach, which implies the self-dispatching of commercial flows of market participants within and between bidding zones in four market segments: forward, day-ahead, intraday and balancing [3,14,15]. The most transparent segment of electricity markets in Europe is the day-ahead market (DAM). Legally, this segment was formalized in 2015 with the adoption of Regulation (EU) 2015/1222, which enshrines the auction mechanism based on the price coupling algorithm (Art. 2, para. 26 and 28) and the use of the marginal pricing principle (Art. 38) and specifies the gate opening time (at the latest 11:00 market time day-ahead) and the gate closure time (at 12:00 CET) [16]. This has provided for establishing a single market price for a bidding zone (for a specific timeframe and all accepted bids), made DAM indicative for other segments of the electricity markets and the day-ahead prices comparable over time and space. Following Regulation 2015/1222, European states are almost unanimous in their choice of forms of trading on DAMs, which function as a double-sided auction with marginal pricing [17].

However, marginal pricing, which is the basic method used in the market, has created conditions for persistent dispersion of electricity prices in search for market equilibrium. For example, according to ENTSO-E Transparency Platform, in 2020, hourly day-ahead prices in Europe ranged from -115 EUR/MWh to 449 EUR/MWh, while average annual day-ahead prices ranged from 8.9 EUR/MWh to 46.7 EUR/MWh in 40 European bidding zones (Appendix A) [18]. In this regard, the question arises about the causes of such dispersion in electricity prices in the European space.

In 2020, the behaviour of electricity prices in Europe was significantly influenced by fundamental factors noted in the European Commission Electricity Market Report (fourth quarter 2020), namely restrictions on economic and social activity, good weather conditions, favourable gas price and volatility of carbon prices [19]. However, these factors together affected all electricity markets, determining the general price behaviour in the European space. Along with this, among other drivers affecting the dispersion of electricity prices in Europe, the report mentions electricity generation mix and cross-border flows [19]. It is precisely these factors, as the authors see it, that put in motion commercial patterns in electricity markets (in bidding zones) and cause the price dispersion in the European space.

The complexity and ambiguity of the factors affecting the dispersion of electricity prices in the European space determine the interest in studying them. In this paper, we attempt to assess how these factors influence the dispersion of electricity prices in the European market space. At each stage of the analysis, the task to reduce the price dispersion in electricity markets of a certain group of countries in terms of each factor is set.

This paper is organized as follows. Section 2 includes a literature review as a theoretical background of this research. Section 3 presents the materials and methods used. The data on day-ahead prices, scheduled commercial exchanges, cross-border physical flow, and actual generation per production type are collected from ENTSO-E Transparency Platform by bidding zones (some countries, e.g., France and Romania, were excluded from the analysis due to lack of data on this platform as of the date of submitting the article).The methodology subsection describes a process of examining price dispersion within geographical boundaries of electricity markets with different market conditions. Section 4 focuses on the results obtained at determining causes of price dispersion in European Electricity Markets. Section 5 presents the discussion and summarizes the main findings of this paper.

2. Literature Review

The theoretical basis of our research is the theory of price dispersion (Stigler (1961)), which states that it arises as a consequence of instability in market supply and demand conditions [20]. The work laid the foundation for a large number of studies that try to explain price dispersion as an equilibrium phenomenon [21]. For example, Reinganum (1979) expressed an idea that, given the firms' distribution of marginal costs, firms' behaviour as monopolistic competitors result in their offering a distribution of prices, which is consistent with expected utility maximization by buyers and with expected profit maximization by sellers [22]. Nowadays, equilibrium price distribution is achieved due to the triangulation of competition intensity, consumer search and firms' pricing decisions [23].

The desire to create competitive electricity markets and establish uniform electricity prices in an integrated market space has resulted in extensive research from scientists from all over the world on dispersion of electricity prices, with the focus on its causes. For example, Wolak (2007) investigated electricity markets in England and Wales, Sweden and Norway, the state of Victoria in Australia, and New Zealand to determine across-country relationship between market rules and market structure and spot prices [24]. Later, Wolak and Tanger (2017) identified distribution effects of charging customers at different locations different prices for electricity [25].

A number of works analyse fundamental factors that determine the price level in electricity markets. Benini, Marracci, Pelacchi, Venturini (2002), using the example of four electricity markets (Spain, California, UK and PJM markets), single out the following factors: fuel prices, availability of generating units, hydro generation production, demand elasticity and variations, network congestion and management rules [26]. Hirth (2018), explaining the reasons for the sharp drop in electricity prices in the EU in 2015, names the following factors: the expansion of renewable energy; the near collapse of the European emissions trading scheme; over-optimistic power plant investments; a decline in final electricity consumption; and cheap coal and natural gas [27]. Mosquera-López, Nursimulu (2019) show that in the case of the spot market, the determinants of prices are renewable infeed and electricity demand, while in the futures market the main drivers are natural gas, coal, and carbon prices [28].

A series of works deal with price volatility in electricity markets. Li, Flynn (2004) examine electrical power price variation for 14 deregulated markets and determine power price volatility through the price velocity [29]. Huisman, Huurma, Mahieu (2007) examine the behaviour of day-ahead hourly prices using a panel model for three European wholesale power markets (the Netherlands, Germany, and France) and show that hourly electricity prices in day-ahead market mean-revert around an hourly specific mean price level, but the speed of mean-reversion is different over the hours [30]. Boži'c, Dobromirov, Arsić, Radišić, Ślusarczyk (2020) investigate volatility on Southeast Europe markets. They find their correlation with developed European markets and show that young electricity markets are, on average, twice as volatile in comparison with more mature markets [31].

Works of some scientists deal with the explanation of the reasons for the convergence or divergence of prices in electricity markets. Bosco, Parisio, Pelagatti, Baldi (2010) analyse long-run relations in European electricity prices and find the existence of interdependencies in wholesale electricity prices in four highly integrated central European markets (France, Germany, the Netherlands, and Austria) [32]. Gugler, Haxhimusa, Liebensteiner (2018) investigate European electricity day-ahead spot prices and combine them with other relevant data, such as hourly interconnector capacities and the existence of market coupling [33]. Australian scientists study a similar problem. It is worth mentioning Apergis, Baruník, Lau, Chi (2017), who explore symmetric price volatility connectedness across states, argue Australian electricity markets are connected asymmetrically, implying the presence of some degree of market power that is exercised by generators across regional electricity markets [34].

Scientists also associate price fluctuations on electricity markets with seasonal factors. Mayer, Trück (2018) examine wholesale electricity spot prices with regard to seasonal patterns, volatility, and the occurrence of price spikes and compare market design and production characteristics [35]. Li, Cursio, Jiang, Liang (2019) assess the influence of calendar effects on the electricity prices [36].

There is also various research on the impact of individual sources of generation [37–39] and demand [40] on electricity prices. However, the scientists failed to find an answer to the question of why the dispersion of electricity prices in the European space is more than 100%. Causes of such dispersion in electricity prices are the subject of this article and associated with differences in the conditions in electricity markets (their geographic orientation, direction of electricity flows and structure of electricity generation), which determine both the convergence of prices on individual national electricity markets and spatial price discrimination.

The concept of price convergence says that, in an efficient market, there must be only one price for commodities regardless of where they are traded [41]. To assess the convergence of prices in electricity markets, indicators of Time Series Analysis [42], β-convergence and a cointegration test [43], correlation analysis between neighbouring markets [44], unit root tests [45], and other techniques are used. In this work, price convergence is considered as a tool for determining the geographical boundaries of electricity markets. For this purpose, correlation analysis [46] and transitive closure [47] are applied. The combination of these two methods, according to the authors, makes it possible to determine the geographical boundaries of electricity markets that mutually influence each other.

The concept of spatial price discrimination represents the ability of a firm to charge different prices to consumers at different locations in space [48]. It is traditionally considered that spatial price discrimination results from difference in transportation costs [49]. However, electricity markets have gone through unbundling, therefore, transmission tariffs are charged separately from the wholesale electricity prices. From a different point of view, according to Hunold, Muthersb (2019), spatial price discrimination may arise due to capacity constraints: each supplier exclusively serves its home market in equilibrium, but cross-supplies result in only partial efficiency [50]. In electricity markets, it is these constraints (related to both generating and transmission capacities) that determine spatial price discrimination and are one of the key reasons for price dispersion in the European space.

Thus, scientists identify various causes of dispersion of electricity prices, associating it with fundamental factors, seasonal factors, volatility of electricity, or integration processes. We are trying to assess how spatial differences in market conditions determine the dispersion of electricity prices over a certain period of time. Among such causes of price dispersion, there are geographical boundaries of electricity markets, direction of electricity flows, and structure of power generation.

3. Materials and Methods

The goal of the study is to find evidence (statistical) confirming or refuting the hypothesis about the influence of geographic orientation and conditions of electricity markets on the dispersion of electricity prices in the European space. The general design of the research is presented in Table 1.

Table 1. Research design.

Hypothesis	Tasks	Theoretical Background	Method	Database [1]
Electricity prices are dispersed in the European space	Assessing quartiles of price electricity dispersion by bidding zones in the European space	Price dispersion	Statistical analysis	Day-ahead prices
Market integration reduces price dispersion	Determining geographical boundaries of the electricity markets	Price convergence	Correlation analysis Transitive closure	Day-ahead prices, scheduled commercial exchanges
Price dispersion on electricity markets is caused by their market conditions	Clustering bidding zones with similar parameters of physical flows of electricity	Spatial price discrimination	Cluster analysis	Cross-border physical flow Actual generation per production type
Price dispersion across electricity markets is a consequence of a simultaneous action of several causes	Constructing a positioning matrix of electricity markets by causes of price dispersion	-	Positioning matrix	Results of the previous research

[1] All data are collected from ENTSO-E Transparency Platform by 40 European bidding zones for 2020 [18], using the Microsoft Excel add-in package—Power Query.

To analyse the dispersion of electricity prices, descriptive statistics [51] and quartile analysis [52] are used. Descriptive statistics allows to prove the hypothesis about dispersion of electricity prices, using such measures as coefficient of variation (the higher the coefficient of variation, the greater the standard deviation of electricity prices to the mean), coefficient of kurtosis (if the coefficient of kurtosis is greater than 3, the distribution of electricity prices is peaked, otherwise it is flat), coefficient of skewness (if the coefficient of skewness is greater than 0, then the asymmetry is left- skewed and more often electricity prices are less than the mean). The quartile analysis implies the distribution of electricity prices in the European space by quartile for each hour during the analysed period. For each bidding zone, the probability of falling into each quartile is established. The belonging of a bidding zone to a certain quartile is conditioned by the greatest probability. For each quartile, the price dispersion is calculated.

To determine geographical boundaries of electricity markets, correlation analysis [53,54] and transitive closure [55] are used. First, 2 matrices—the matrix of scheduled commercial flows and the correlation matrix of bidding zone electricity prices—are built. The presence of scheduled commercial flows and a high correlation between electricity prices condition the inclusion of the bidding zone in the final adjacency matrix. Using the adjacency matrix, the transitive closure of the subgraphs is determined, which is the basis for connecting the geographical boundaries of the bidding zones. Electricity markets are divided into adjacent zones by levels:

- Commercially integrated markets, i.e., those between which there are commercial flows of electricity;
- Highly integrated markets, i.e., commercially integrated bidding zones the correlation between which is equal to or greater than 0.9;
- Moderately integrated markets, i.e., commercially integrated bidding zones the correlation between which is within the range from 0.8 to 0.9;

- Poorly integrated markets, i.e., commercially integrated bidding zones the correlation between which is within the range from 0.7 to 0.8;
- Non-integrated markets, i.e., commercially integrated bidding zones the correlation between which is less than 0.7.

The price dispersion is calculated for each geographic market.

The clustering of bidding zones with similar parameters of physical flows of electricity is carried out in two stages. First, electricity markets are clustered based on the direction of electricity flows, which depends on the share of import and export flows of electricity, as well as domestic generation in the total electricity consumption. At the second stage, a cluster analysis based on the structure of electricity generation is carried out. The clustering is performed with the help of two methods: hierarchical clustering and k-means algorithm with the use of IBM SPSS Statistics [56]. Bidding zones belong to a specific cluster if the two clustering methods give the same results, which can be seen from the contingency table. The price dispersion is calculated for each cluster. For this case, the electricity prices were not directly used in cluster analysis as an individual variable but were superimposed upon its results. To finalize the research results, a positioning matrix, which is widely used in strategic management, is employed [57,58]. For the purposes of our research, we build a three-dimensional positioning matrix, the axes of which are the investigated causes of price dispersion. The average annual electricity prices are superimposed upon the resulting distribution. As a consequence, the expected result of the study is the visualization of a gradual increase in the distribution of electricity prices in the European space in three dimensions, as we move between the matrix quadrants (right, upward and inward).

4. Results

4.1. Price Dispersion Results

The instability of conditions of the electricity markets in the European space (primarily in terms of the demand), due to the COVID-19 pandemic, caused a sharp dispersion in electricity prices in 2020 (Appendix A, see the acronyms for the bidding zones in Supplementary Materials). The distribution of electricity prices in the European space was uneven: highly variable (the coefficient of variation was 0.63), peaked (the coefficient of kurtosis was 5.95), and right skewed (the coefficient of skewness was at the level of 1.01). At the same time, the electricity price variation between European bidding zones fluctuated from 0.27 (PL) to 0.91 (SE3). In most bidding zones, there was a peaked distribution of prices (the sharpest one was in GB and IT Sardinia) and only in ES and PT flat distribution was observed. Left skewness was in the bidding zones of DE-LU, ES and PT, whereas the highest level of right skewness was observed in the bidding zones of EE, FI, GB, SE1-SE4, SEM. Extreme prices were often recorded in the European bidding zones: they 1821 times fell below 0 Euro/MWh (most often in the bidding zones of SEM, DE-LU, DK1), and 1643 times exceeded 100 Euro/MWh (most often in the bidding zones of IT Sicily, SEM, HU). Based on this, the authors assume a wide dispersion of electricity prices both within one bidding zone and within one bidding interval between different bidding zones.

The results of the quartile analysis indicate a significant dispersion of prices between the 1st and 4th quartiles in all bidding zones (the greatest value is observed in BE, CZ, SK - more than 150%, the smallest one is in PL, ES, PT, RS—up to 100%). While the interquartile range is significantly smaller (the largest one is in the Norwegian and Swedish bidding zones—up to 85%, the smallest one is in ES, PT, GR, GB, PL, in individual zones of Italy—up to 40%).

The analysis of the price dispersion over time makes it possible to determine the belonging of the bidding zones to certain quartiles, according to the maximum probability of falling into a certain quartile (Table 2, Appendix B).

Table 2. Distribution of European electricity markets by price quartiles in 2020.

Quartile	Bidding Zones	Average Annual Electricity Price by Quartile, EUR/MWh	Price Range within Quartile, %	Coefficient of Variation Max	Coefficient of Variation Min
Q1	DK1, EE, FI, LT, LV, NO1, NO2, NO3, NO4, NO5, SE1, SE2, SE3, SE4	19.76	283	0.61	0.91
Q2	AT, BE, CZ, DE-LU, DK2, ES, NL, PT, SK	32.41	20	0.33	0.69
Q3	CH, HR, IT C.-N., IT C.-S., IT N., IT Sar., IT South, SL	37.97	17	0.38	0.44
Q4	BG, GB, GR, HU, IT Sic., PL, RO, RS, SEM	41.32	24	0.26	0.61

Source: calculated by authors based on ENTSO-E Transparency Platform database of day-ahead prices [18].

The lowest electricity prices were most often recorded in Norway (NO1—36%, NO3—13%, NO4—15% of all cases in the period under study), in DK1—11%, DE-LU—6%. The highest prices were recorded in PL—24%, IT Sicily—21%, GR—18%, SEM—7%, EE—6%.

Q1 comprises 14 bidding zones, including those of the Nordic and Baltic countries, as well as DK1. The probability of the falling of the Norwegian and two Swedish bidding zones (SE1 and SE2) into the quartile exceeded 90%, whereas that for SE3 and SE4 was 80% and 59%, respectively. DK1 and FI were assigned to Q1 with an approximate 50% probability. Whereas the bidding zones of the Baltic countries had the lowest probability, which was in the case of EE—32% and LT and LV—29% for each. The probability values determined the dispersion in average annual electricity prices within this quartile. On the Norwegian electricity markets, prices were within the range of 8.88–9.46 EUR/MWh; on the Swedish ones—14.39–25.86 EUR/MWh; on those of DK1 and FI–24.99 EUR/MWh and 28.02 EUR/MWh, respectively; on the Baltic ones—33.69–34.05 EUR/MWh. Q1 is characterized by the absence of sharp negative price spikes, which occurred mainly in DK1 (192 h), while sharp positive spikes occurred in EE (67 times), FI (58 h), SE3 (47 h) and SE4 (49 h). Despite the low frequency of price extremes, prices in the bidding zones belonging to Q1 had the greatest variation.

Q2 comprises 9 bidding zones, mainly markets of CWE countries, including Iberian Electricity Market (MIBEL) and that of Slovakia. The markets that make up the heart of this region—DE-LU, NL, BE, AT—had the highest probability of falling into this quartile (about 60%). With distance from the centre of the CWE region, the probability decreased and amounted to 45% for CZ, 44% for SK, 40% for DK2, and 35% for MIBEL. In Q2, the average price was 32.41 EUR/MWh, however, compared to Q1, the dispersion of prices within this quartile did not depend on the probability and amounted to 30.47–33.15 EUR/MWh for the bidding zones with the highest frequency, 28.41–34.01 EUR/MWh—with the middle one, 33.96–33.99 EUR/MWh—with the low one. At the same time, negative price spikes were more frequent (965 spikes in total), whereas positive price spikes were smoother and rarer (only 222 spikes). Compared to Q1, Q2 is characterized by smaller variation, within 33–69%.

Q3 comprises 8 bidding zones including those with more than a 50% probability (IT North, IT Centre-North, HR and SL), with more than a 40% probability (IT Centre-South, IT South), and with a probability of slightly less than 40% (CH). The dispersion of electricity prices amounted to 34.00–39.67 EUR/MWh and was determined by both the probability of falling into this quartile and the probabilities of falling into the neighbouring quartiles. Thus, if for CH the probability of being assigned to Q3 was 39%, to Q2—38%, and Q4—16%, the value of the average annual price was the smallest and amounted to 34.00 EUR/MWh in this quartile. Whereas for IT Centre-South the average annual price (39.67 EUR/MWh) was due to a 44% probability of falling into Q3, 30% probability of falling into Q4, and 22% probability as concerns Q2. In this quartile, there were practically no negative (most often in CH—75 h) and positive (most often in HR—55 h) price spikes. The price variation was the lowest compared to other quartiles (from 38% to 44%).

Nine bidding zones are assigned to Q4. PL and GR had the highest probability of falling into this quartile, 76% and 67%, respectively. The probability for other bidding zones was within 40-50%. The dispersion of average annual prices within the quartile was from 37.07 to 46.66 EUR/MWh. The lowest price within this quartile was in SEM, which had a probability of 43% of falling into Q4 but also a significant probability of falling into Q1 (17%), due to a high price variation (at the level of 61%). The highest average annual price was recorded in PL, the probability of falling into Q1 was 0%, into Q2—7%, Q3—16%, the price variation being the lowest in the European space (26%). Negative price spikes were recorded only in SEM (374 h) and GB (91 h), while positive price spikes were infrequent but recorded in all bidding zones except PL. With the exception of PL, this quartile shows an increase in price variation over time compared to Q2 and Q3.

Thus, the results of the quartile analysis allow to confirm the hypothesis about the dispersion of prices in the European space and are the basis for finding the causes of this dispersion.

4.2. Price Dispersion within the Geographical Boundaries of Electricity Markets

The EU seeks to create a single electricity market across Europe by developing cross-border power grids and introducing market coupling mechanisms. However, European bidding zones remain insufficiently physically integrated to create a single European electricity market. So, we will investigate how the integration of electricity markets affects price dispersion in the European space. To do this, it is necessary to identify the geographic boundaries of electricity markets and determine how the price range will decrease in the bidding zones belonging to the same geographical market. For this purpose, the matrices of scheduled commercial exchanges and the correlation matrix of day-ahead prices are constructed (see Supplementary materials). When determining the geographical boundaries of electricity markets, the following conditions are considered: firstly, the presence of commercial electricity flows between two bidding zones and, secondly, high correlation values between two bidding zones.

The analysis of these groups of markets was carried out using transitive closure, since adjacent zones can interact not only with their neighbours but also with the neighbours of their neighbours, expanding geographical boundaries beyond the adjacent zones.

The results of the transitive closure (Table 3, Appendix C) have allowed to single out four groups of electricity markets by the level of integration.

Table 3. Price dispersion by geographical electricity markets in 2020.

Bidding Zones	Average Annual Electricity Price, EUR/MWh	Price Range, %	Coefficient of Variation		Market Quartile Range
			Max	Min	
Highly integrated markets					
AT, CH, CZ, DE-LU, SK	33.04	12	0.43	0.57	2–3
BE, NL	32.06	1	0.48	0.52	2
DK2, SE3, SE4	25.15	34	0.69	0.91	1–2
EE, LT, LV	33.93	1	0.61	0.64	1
ES, PT	33.97	0	0.33	0.34	2
HR, HU, RS, SL, RO, IT N, IT C-N, IT C-S, IT S, IT Sar	38.72	10	0.38	0.45	3–4
NO1, NO2, NO3, NO4, NO5	9.22	7	0.73	0.89	1
SE1, SE2	14.39	0	0.80	0.80	1
Moderately integrated markets					
AT, HU, SL, SK	35.93	18	0.43	0.48	2–4
BE, DE-LU, CH, CZ, DK1, DK2, NL	30.73	36	0.43	0.70	1–3
BG, RO, RS	39.21	1	0.42	0.45	4
EE, FI, SE3	27.63	59	0.64	0.91	1
GB, SEM	38.53	5	0.47	0.61	4
IT S, IT Sicily	42.61	18	0.38	0.51	3–4
Poorly integrated markets					
BE, GB, NL, DK1, SE3	29.98	87	0.21	0.4	1–4
DE-LU, DK2	29.44	7	0.28	0.30	2
LT, PL, SE4, SK	35.14	80	0.26	0.47	1–4
Non-integrated markets					
GR	45.09	-	0.38		4

Source: calculated by authors based on ENTSO-E Transparency Platform database of day-ahead prices and scheduled commercial exchanges [18].

Eight strongly connected subgraphs, each of which can be defined as a geographical electricity market. Among these markets, the market of South-Eastern Europe (SEE), which includes 10 bidding zones, and that of Central-Western Europe (CWE), which consists of five bidding zones, are the largest by area. A separate market was formed by the bidding zones of the Baltic countries. The Norwegian bidding zones merged into a single market, while the Swedish market was split in half: into SE1 and SE2, and SE3 and SE4, which merged with DK2. BE with NL and ES with PT (MIBEL) and formed two separate markets. The geographical electricity markets defined in this way have a low range of prices (up to 34%) and are characterized by their relatively equal variation.

Six moderately connected subgraphs the bidding zones, of which are quite open for their neighbours. These are the bidding zones of Central-Eastern Europe (HU, SL, SK), which are partially integrated with the CWE market through the AT bidding zone. BE with NL and DK1 with DK2 also have moderate commercial links with the CWE market. BG seeks to integrate into the SEE market through the RO and RS bidding zones, while EE and FI seek to integrate into the Northern market through SE3. SEM and GB are also trying to create a single electricity market in the British Isles. IT Sicily has moderate links with the main part of Italy through the IT South bidding zone. These markets have a high price range (up to 60%) and a significant deviation of variation.

Three poorly connected subgraphs the bidding zones, of which have limited opportunities of market trading with the neighbouring ones. GB is trying to integrate into the electricity market of continental Europe through the BE and NL bidding zones while the latter is trying to become part of the Swedish market through DK1 and SE3. The gradual opening of commercial trade is taking place between DE_LU and DK2. The PL bidding zone, which is developing trade both with the CWE and the Nordic countries, is characterized by weak but diversified commercial ties. In this group, there is an even greater price range (up to 87%) and a sharp deviation of variation.

One isolated subgraph formed by the GR bidding zone that has no significant commercial interaction with other ones.

Thus, the hypothesis of a decrease in the dispersion with an increase in the integration of electricity markets is considered to be confirmed. In case of highly integrated markets, the dispersion is within 1–2 quartiles, for moderately integrated markets—1–3 quartiles, and for poorly integrated markets—1–4 quartiles. In addition, highly integrated markets often fall into the lower quartiles, while poorly integrated and non-integrated markets are in the upper quartiles.

4.3. Interrelation of Physical Orientation of Electricity Markets and Price Dispersion

It is impossible to find two identical electricity markets, neither in Europe nor in the whole world. They differ both in the structure of demand and in the structure of supply. Various types of generations differ in the marginal cost of electricity, while electricity itself differs in consumer value in different periods of time. The study proves that a significant cause of the price dispersion on the electricity markets is their different physical orientation, in particular, the structure of generation and the direction of flows. The paper presents the results of a cluster analysis carried out in two stages (for certain reasons), the purpose of which was to reduce the price dispersion in each cluster.

First, a cluster analysis of the direction of electric energy flows was carried out (Table 4). Figure A1 (Appendix D) presents the structure of electricity flows in the European space in 2020, which confirms the heterogeneity of the markets in terms of their openness and self-sufficiency.

The first cluster comprises export-directed markets. The participation in cross-border trade allowed them to sell expensive production surplus to other countries while importing low-price bids. This can be considered the cause of both a sharp price variation and large price range within the cluster 2 of these markets (NO and SE) assigned to Q1, 3 (AT, CZ, SK)—to Q2, 1 (SL)—to Q3.

Table 4. Clustering of electricity markets by direction of flows in 2020.

Cluster Name		Export-Directed	Import-Directed	Inward-Directed
Countries		AT, CZ, NO, SE, SK, SL	CH, DK, EE, HR, LT, LV	BE, BG, DE with LU, ES, FI, GB, GR, HU, IE, IT, NL, PL, PT, RO, RS
Mean values inside the cluster, %	Import	40	68	10
	Export	46	45	13
	Net generation	119	67	93
Average annual electricity price, EUR/MWh		20.01	32.46	37.88
Price range, %		323	52	67
Coefficient of variation	min	0.43	0.43	0.26
	max	0.90	0.70	0.75
Distribution by quartiles, %	Q1	33	57	7
	Q2	50	14	33
	Q3	17	29	7
	Q4	0	0	53

Source: calculated by authors based on ENTSO-E Transparency Platform database of cross-border physical flow, actual generation per production type and day-ahead prices [18].

The second cluster comprises import-directed markets, on which the volume of electricity imports prevailed over exports. However, even with an insufficient level of their own generation, these countries transmitted significant flows of electricity across their borders in both directions. The variation of prices was high but considerably less than that in the first cluster. The openness of the borders of the national electricity markets allowed them to benefit from market trading. As a consequence, four bidding zones (DK1, EE, LT, LV) were assigned to Q1, 1 zone (DK2)—to Q2, and 2 (CH, HR)—to Q3. The price range in this cluster was the least among all.

The third cluster includes inward-directed countries, which were characterized by insignificant volumes of cross-border trade. This forced them to assume all the risks of covering the costs of internal generation, as a result of which the average price of electricity in this cluster turned out to be the highest. Among these countries, only 1 (FI) was assigned to Q1, 4 of them (BE, DE-LU, ES, NL)—to Q2, and 1 country (IT)—to Q3 while the rest of them—to Q4.

Thus, it can be partially confirmed that the direction of electricity flows determines the dispersion of electricity prices in the European space. It especially affects import-directed markets while export-directed and especially inward-directed markets are significantly dependent on internal electricity generation sources. The price range in the first and third clusters confirms the discriminatory nature of marginal pricing over space.

At the second stage, a cluster analysis of European electricity markets in terms of structure of internal generation was carried out (Table 5). Figure A2 (Appendix D) shows the structure of internal electricity generation in European countries in 2020.

Table 5. Clustering of electricity markets by generation structure in 2020.

Cluster Name		Hydro Generated	Nuclear Generated	RES Generated	Gas Generated	Coal Generated
Countries		AT, NO	BE, CH, FI, HU, SE, SK, SL	DE with LU, DK, EE, LT	ES, GB, GR, HR, IE, IT, LV, NL, PT	BG, CZ, RS, PL
Mean values inside the cluster, %	Hydro	87	24	4	14	11
	Nuclear	0	40	2	5	22
	RES	12	11	28	24	7
	Gas	8	10	6	34	6
	Coal	0	7	8	6	54
Average price of electricity, EUR/MWh		21.18	28.03	30.32	38.23	39.60
Price range, %		259	171	36	43	39
Coefficient of variation	min	0.48	0.43	0.58	0.33	0.27
	max	0.82	0.91	0.70	0.61	0.48
Distribution by quartiles, %	Q1	50	29	70	13	0
	Q2	50	29	30	37	25
	Q3	0	29	0	13	0
	Q4	0	14	0	37	75

Source: calculated by authors based on ENTSO-E Transparency Platform database of actual generation per production type and day-ahead prices [18].

The results of clustering European electricity markets by structure of internal generation have made it possible to identify five clusters, the name of which was chosen based on the dominant type of power generation.

The first cluster comprises two countries characterized by a high share of hydroelectricity. In this cluster, the electricity prices are low but vary significantly since the markets belong to Q1 and Q2;

The second cluster includes seven countries that use mainly nuclear generation. Compared to the first cluster, here, the average price is higher, and the price range is lower but still significant. In terms of price dispersion, the countries are most often assigned to from Q1 to Q3, less often to Q4;

The third cluster comprises four countries with highly developed RES generation. In this cluster, average prices are higher compared to the first two, but the price range is the lowest, the variability being usually high. Most often the countries belong to Q1, and sometimes to Q2;

The fourth cluster is made by eight countries dominated by gas-fired generation. In this cluster, there is also a significant decrease in the price range and variation, but in terms of price range the countries belong to each of the quartiles;

Four countries dominated by coal-fired generation are assigned to the fifth cluster. These countries also show a narrowing price range and the lowest variation. The average prices are high, and the countries are most often in Q4.

Thus, a significant decrease in the price dispersion can be noted in the countries that rely on hydrocarbon and green generation, whereas in the countries that produce electricity using mainly hydro or nuclear power, a significant price dispersion is observed.

4.4. Constructing Positioning Matrix of Electricity Markets by Causes of Price Dispersion

At the last stage of the study, it is advisable to combine the individual causes of the price dispersion and determine whether it is possible to reduce it if all the three factors (geographical orientation, flow direction and generation structure) are simultaneously considered. For these purposes, a positioning matrix is used. Figure 1 presents a three-dimension positioning matrix, the axes of which are the examined causes, which in turn are divided into certain quadrants by groups.

The positioning results show the splitting of electricity markets in the European space into the following levels.

The first level is made up of export-directed markets. The Norwegian markets (quadrant $1 \times 1 \times 1$) have the cheapest electricity generated from hydro sources, whereas in the AT bidding zone (quadrant $1 \times 1 \times 5$), there is a sharp increase in electricity prices. A similar trend is observed when moving upward. Thus, the Swedish market (quadrant $1 \times 2 \times 2$) is characterized by a twofold increase in the price of electricity in comparison with the Norwegian one. On the Slovak market (quadrant $1 \times 2 \times 5$), which is focused on nuclear energy and belongs to the CWE market, the electricity price is even higher than on the Swedish one. Additionally, the Slovenian market (quadrant $1 \times 2 \times 8$), which already belongs to the SEE, is characterized by an increase in prices compared to the Slovak one.

The second level is made up of import-directed markets. For example, the cheapest electricity is produced from RES in Denmark (quadrant $2 \times 3 \times 3$), whereas in Switzerland ($2 \times 2 \times 4$ quadrant), although it is mostly generated from nuclear sources, it is more expensive since the country belongs to the CWE market. The most expensive electricity is on the Baltic markets, in particular, on the RES-oriented markets of EE (quadrant $2 \times 3 \times 7$) and LT (quadrant $2 \times 3 \times 7$), and the gas-oriented one of LV (quadrant $2 \times 3 \times 8$).

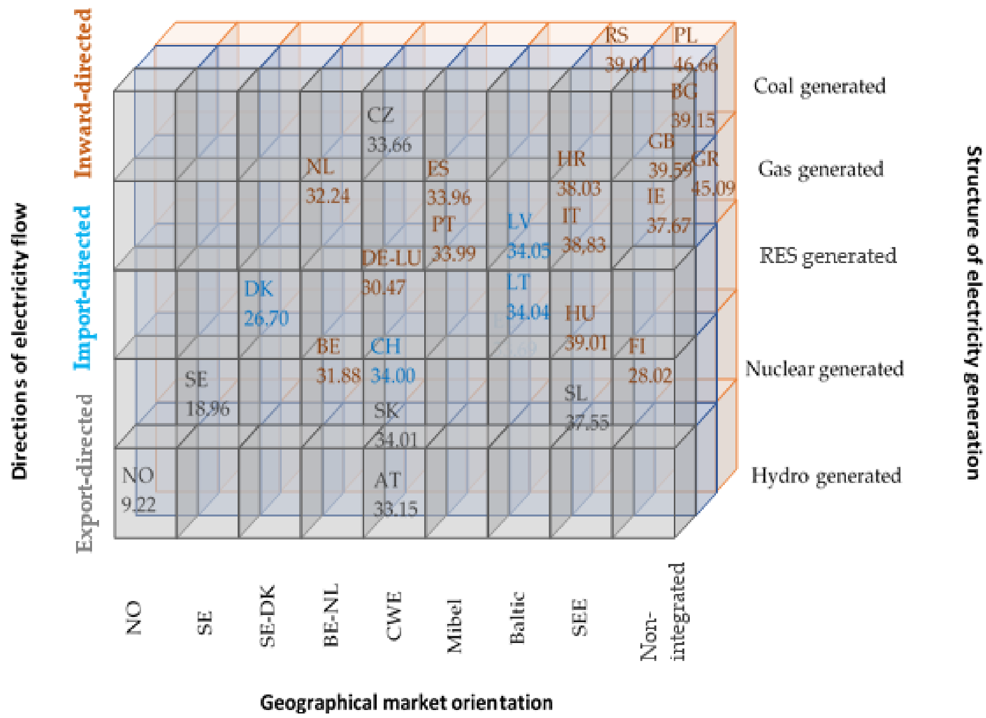

Figure 1. The matrix of dispersion of electricity prices in Europe in the three-dimensional space "geographic orientation–flow direction–generation structure". Notes: in terms of geographic orientation, only highly integrated markets are considered. Source: constructed by the authors based on the above research results.

The third level is inward-directed markets. For example, in the BE nuclear-oriented market (3 × 2 × 4 quadrant), electricity is cheaper than in the NL gas-oriented market (3 × 4 × 4 quadrant). On MIBEL (quadrant 3 × 4 × 6), the price of electricity is higher than that on the NL market, whereas on the SEE markets (quadrant 3 × 4 × 8), there is an extra increase in prices. The most expensive electricity is on the Serbian market (3 × 5 × 8 quadrant), which geographically belongs to the SEE market and uses coal as a source for electricity generation.

On non-integrated markets, there is an even greater price increase (BG, GR, GB, PL) or price dispersion (IE, FI). The most expensive electricity is on the poorly integrated, inward-directed coal electricity market in Poland.

In this matrix, the markets of CZ (quadrant 1 × 5 × 5), DE-LU (quadrant 3 × 3 × 5), and HU (quadrant 3 × 2 × 8) can be considered as exceptions. It can be assumed that they are significantly influenced by other sources of generation (nuclear generation for CZ and gas generation for HU), or integration relations (DE-LU is moderately integrated with both BE and NL, and DK markets).

In general, the results of the study showed the presence of evidence (statistical) confirming the hypothesis about the influence of the identified causes of the price dispersion on the electricity markets. The most significant influence is exerted by the geographical orientation of the markets while the structure of generation goes second, and the direction of flows is in third place.

5. Discussion and Conclusions

The existence of price dispersion in European electricity markets is conditioned by the accepted market model (based on marginal pricing) and is due to their heterogeneity. The paper analyses the price dispersion in 40 European bidding zones (electricity markets) and determines the price quartiles they belong to. It has been found that the markets with cheap electricity, which are assigned to Q1 and Q2, demonstrate a higher variation. Whereas the markets with expensive electricity, which belong to Q3 and Q4, demonstrate a low variation. The paper assumes and proves that the dispersion of electricity prices in the European space is conditioned by geographic orientation of national markets, direction of electricity flows and structure of generation. As a result of the study, the dispersion of electricity prices was determined both for each of the factors under study and for the complex of these factors.

To determine the geographical boundaries of the regional electricity markets, a correlation analysis of prices in the European space was carried out. The results of the analysis were superimposed upon the matrix of cross-border commercial electricity flows, and, using an adjacency matrix, the transitive closure of borders between national markets was determined. The research results allowed to identify eight highly integrated markets, six moderately integrated, three poorly integrated ones, and one non-integrated market. We can note that there is a significant reduction in the dispersion on highly integrated markets. At the same time, moderately integrated and especially poorly integrated markets demonstrate a larger price dispersion.

In order to determine the direction of electricity flows of the electricity markets in the European space, a cluster analysis, considering the share of exports/imports and share of internal generation in electricity consumption, was carried out. This made it possible to single out export-directed, import-directed, and inward-directed electricity markets. It has been proven that export-directed markets most often belong to Q2 (since they rely only on internal generation), whereas import-directed markets belong to Q1 and benefit from market trading. As concerns inward-directed markets, they are assigned to each of the quartiles since they must cover all price risks themselves.

The clustering of electricity markets by structure of electricity generation (by share of generation in the structure of electricity consumption) has made it possible to identify five clusters: hydro, nuclear, RES, gas and coal electricity markets. The lowest prices and the smallest price dispersion (Q1–Q2) are in the hydro and RES electricity markets. The largest price dispersion is on the nuclear and gas electricity markets (Q1–Q4) while on the coal electricity markets it covers Q2–Q4.

The construction of a three-dimensional matrix has made it possible to combine the three identified causes for the price dispersion and show how, as we move through the matrix quadrants (to the right, upward and inward), the electricity prices increase. It can be seen that the cheapest electricity is on the export-directed Norwegian hydro electricity markets, while the most expensive is on the inward-directed poorly integrated coal electricity market in Poland.

Thus, the study has allowed to prove the existence of three causes of the spatial dispersion of electricity prices in the European space. The dispersion of prices can also be caused by other factors. However, as suggested by the authors, they more determine the dispersion of electricity prices over time.

Estimating price dispersion is an important task for creating a competitive electricity market. The presented approach will be useful for policymakers who are responsible for strategic decisions concerning the development of electricity markets. Reducing electricity prices is possible due to:

The development of internal capacities of non-fossil generation. Especially hydro and green generation, which can greatly influence the belonging of the bidding zone to a certain price quartile, while nuclear generation imposes certain constraints to price reduction;

The identification of promising directions of integration. Opening the boundaries of electricity markets can also change the price quartile of certain bidding zones. Moreover, it can reduce price dispersion with the neighbouring bidding zones;

Proper choice of directions of electricity flows, which is allowed to hedge the risks of the internal volatility of the marginal electricity price.

All these causes must be considered by policymakers in combination since they have a synergy effect on the prosperity of electricity markets.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132212343/s1, Table S1: Correlation matrix for European day ahead electricity prices in 2020, Table S2: Matrix of scheduled commercial exchanges in 2020.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Statistical analysis of the distribution of electricity prices in the European space in 2020.

Bidding Zone	Mean, EUR/MWh	Min, EUR/MWh	Q1, EUR/MWh	Q2 (Median), EUR/MWh	Q3, EUR/MWh	Max (Q4), EUR/MWh	Variation, %	Coefficient of Kurtosis	Coefficient of Skewness
AT	33.15	−77.7	24.08	33.07	42.18	200.0	47.8	6.20	0.28
BE	31.88	−115.3	21.6875	31.5	41.2	200.0	51.9	7.72	0.14
BG	39.15	0.0	27.83771	38.33	50.63146	130.0	45.2	2.20	0.67
CH	34.00	−59.6	24.78	34.59	42.6025	126.7	43.4	3.30	0.27
CZ	33.56	−65.0	23.7175	32.84	42.7	125.1	47.8	2.70	0.44
DE-LU	30.47	−83.9	21.75	30.99	40.25	200.0	57.4	6.55	-0.28
DK1	24.99	−58.8	12.295	23.86	35.8525	200.0	69.8	3.60	0.79
DK2	28.41	−42.7	15.08	25.48	38.82	254.4	69.4	10.52	1.86
EE	33.69	−1.7	18.9675	32.07	45.64	255.0	63.6	13.06	2.04
ES	33.96	1.0	26.45	34.62	42	68.9	33.6	-0.28	-0.24
FI	28.02	−1.7	12.7375	24.11	40.005	254.4	75.4	10.34	2.02
GB	39.59	−43.3	29.89244	38.01	47.44736	387.7	46.7	35.11	2.86
GR	45.09	0.0	34.21	42.58	53	150.1	37.8	2.78	1.09
HR	38.03	−23.5	27.5075	36.97	46.3275	172.1	44.1	6.01	1.26
HU	39.01	−8.1	27.8375	37.205	47.465	150.0	45.1	4.23	1.29
IT Center-North	38.71	0.0	28.5275	38.205	46.8525	163.1	38.2	2.03	0.71
IT Center-South	39.67	0.0	29.39	39.685	48.17	163.1	38.0	1.58	0.55
IT North	37.79	0.0	27.81	37.3	45.84	163.1	38.2	2.25	0.74
IT Sardinia	38.97	0.0	28.5675	39.27	48.1325	449.0	42.2	44.62	1.97
IT Sicily	46.21	0.0	29.0975	41.39	61.685	155.0	50.7	0.25	0.75
IT South	39.00	0.0	28.8775	39.12	47.8125	163.1	38.1	1.12	0.38
LT	34.04	−1.7	19.7425	33.035	45.7425	255.0	61.4	12.49	1.91
LV	34.05	−1.7	19.7775	33.04	45.71	255.0	61.3	12.55	1.91
NL	32.24	−79.2	22.9	31.67	40.19	200.0	47.5	7.06	0.92
NO1	9.29	−1.7	1.99	6.96	13.5525	99.9	89.1	10.02	1.87
NO2	9.29	−1.7	2.13	6.95	13.5525	99.9	88.9	10.10	1.88
NO3	9.46	0.0	3.79	7.5	13.9325	57.0	73.1	0.96	1.03
NO4	8.88	0.0	3.6975	7.42	12.63	57.0	73.0	1.93	1.24
NO5	9.17	−0.1	1.92	6.855	13.5425	99.9	86.2	4.13	1.27
PL	46.66	11.4	38.65	45.64	53.83	147.9	26.5	1.02	0.32
PT	33.99	1.0	26.51	34.64	41.94	68.9	33.1	-0.27	-0.26
RO	39.49	0.0	28.01342	37.8672	48.16876	150.0	44.8	3.88	1.23
RS	39.01	0.9	28.1575	37.56	47.14	165.6	42.4	5.06	1.28
SE1	14.39	−1.7	5.93	12.145	19.9025	189.3	80.0	21.17	2.87
SE2	14.39	−1.7	5.93	12.145	19.9025	189.3	80.0	21.16	2.87
SE3	21.19	−1.7	7.59	16.745	27.865	254.4	91.0	14.20	2.64
SE4	25.86	−2.0	10.07	22.3	37.24	254.4	78.1	9.67	1.92
SEM	37.67	−41.1	27	35.64	45.925	378.1	61.1	18.08	2.23
SK	34.01	−65.0	23.885	33.055	43.1	125.1	48.3	2.46	0.48
SL	37.55	−23.5	27.09	36.6	45.8625	172.1	43.3	5.73	1.15
pan-European	31.10	−115.3	17	30.49	43	449.0	62.8	5.95	1.01

Source: calculated by authors based on ENTSO-E Transparency Platform database of hourly day-ahead prices [17].

Appendix B

Table A2. Distribution of European markets by probability of falling into price quartiles in 2020.

Bidding Zone	The Probability of Falling into Quartile				Belonging to Quartile
	Q1	Q2	Q3	Q4	
AT	8%	59%	32%	1%	2
BE	14%	61%	19%	5%	2
BG	7%	22%	23%	48%	4
CH	7%	38%	39%	16%	3
CZ	8%	45%	33%	13%	2
DE-LU	16%	62%	20%	2%	2
DK1	50%	39%	10%	1%	1
DK2	39%	40%	13%	7%	2
EE	32%	27%	14%	27%	1
ES	17%	35%	26%	22%	2
FI	51%	22%	10%	16%	1
GB	5%	20%	27%	48%	4
GR	4%	12%	17%	67%	4
HR	3%	33%	51%	13%	3
HU	2%	19%	38%	41%	4
IT Center-North	3%	24%	51%	22%	3
IT Center-South	4%	22%	44%	30%	3
IT North	4%	28%	53%	15%	3
IT Sardinia	6%	22%	42%	29%	3
IT Sicily	6%	17%	28%	49%	4
IT South	7%	23%	41%	29%	3
LT	29%	29%	14%	28%	1
LV	29%	29%	14%	28%	1
NL	14%	62%	19%	5%	2
NO1	94%	5%	0%	0%	1
NO2	94%	5%	0%	0%	1
NO3	96%	4%	0%	0%	1
NO4	96%	4%	0%	0%	1
NO5	94%	5%	0%	0%	1
PL	0%	7%	16%	76%	4
PT	17%	35%	26%	22%	2
RO	2%	18%	35%	44%	4
RS	2%	17%	37%	45%	4
SE1	95%	3%	1%	0%	1
SE2	95%	3%	1%	0%	1
SE3	80%	12%	4%	4%	1
SE4	59%	27%	7%	6%	1
SEM	17%	21%	19%	43%	4
SK	7%	44%	34%	15%	2
SL	3%	34%	53%	11%	3

Source: calculated by authors based on ENTSO-E Transparency Platform database of hourly day-ahead prices [17].

Appendix C

Table A3. Determination of adjacent zones in European electricity markets in 2020.

Bidding Zone	Commercially Integrated Bidding Zones		Highly Integrated Bidding Zones		Moderately Integrated Bidding Zones		Poorly Integrated Bidding Zones		Non-Integrated Bidding Zones	
AT	6	CH, CZ, DE_LU, HU, IT N, SL	3	CH, CZ, DE_LU	3	HU, IT N, SL	0	-	0	-
BE	4	DE_LU, GB, NL	1	NL	1	DE-LU	1	GB	0	
BG	3	GR, RO, RS	0	-	2	RO, RS	0	-	1	GR
CH	3	AT, DE_LU, IT N	2	AT, IT N	1	DE_LU	0	-	0	-
CZ	4	AT, DE_LU, PL, SK	2	AT, SK	1	DE_LU	1	PL	0	-
DE-LU	10	AT, BE, CH, CZ, DK1, DK2, NL, NO2, PL, SE4	1	AT	5	BE, CH, CZ, DK1, NL	1	DK2	3	NO2, PL, SE4
DK1	5	DE_LU, DK2, NL, NO2, SE3	0	-	2	DE_LU, DK2	1	NL	2	NO2, SE3
DK2	3	DE_LU, DK1, SE4	1	SE4	1	DK1	1	DE-LU	0	-
EE	2	FI, LV	1	LV	1	FI	0	-	0	-
ES	2	PT	1	PT	0	-	0	-	0	-
FI	3	EE, SE1, SE3	0	-	2	EE, SE3	0	-	1	SE1
GB	3	BE, NL, SEM	0	-	1	SEM	2	BE, NL	0	-
GR	2	BG, IT S	0	-	0	-	0	-	2	BG, IT S
HR	3	HU, RS, SL	3	HU, RS, SL	0	-	0	-	0	-
HU	5	AT, HR, RO, RS, SK	3	HR, RO, RS	2	AT, SK	0	-	0	-
IT C.-N.	1	IT N	1	IT N	0	-	0	-	0	-
IT C.-S.	3	IT C_N, IT Sar, IT S	3	IT C_N, IT Sar, IT S	0	-	0	-	0	-
IT N	2	IT C_N, SL	2	IT C_N, SL	0	-	0	-	0	-
IT Sar.	1	IT C_S	1	IT C_S	0	-	0	-	0	-
IT Sic.	1	IT S	0	-	1	IT S	0	-	0	-
IT South	1	IT C_S, IT Sic	1	IT C_S	1	IT Sic	0	-	0	-
LT	3	LV, PL, SE4	1	LV	0	-	2	PL, SE4	0	-
LV	2	EE, LT	2	EE, LT	0	-	0	-	0	-
NL	5	BE, DE_LU, DK1, GB, NO2	1	BE	2	DE_LU	2	DK1, GB	0	-
NO1	4	NO2, NO3, NO5, SE3	2	NO2, NO5	1	NO3	0	-	1	SE3
NO2	5	DE_LU, DK1, NL, NO1, NO5	2	NO1, NO5	0	-	0	-	3	DE_LU, DK1, NL
NO3	4	NO1, NO4, NO5, SE2	2	NO4, NO5	1	NO1	0	-	1	SE2
NO4	3	NO3, SE1, SE2	1	NO3	0	-	0	-	2	SE1, SE2
NO5	3	NO1, NO2, NO3	3	NO1, NO2, NO3	0	-	0	-	0	-
PL	5	CZ, DE_LU, LT, SE4, SK	0	-	0	-	3	CZ, LT, SK	2	DE_LU, SE4
PT	1	ES	1	ES	0	-	0	-	0	-
RO	3	BG, HU, RS	2	HU, RS	1	BG	0	-	0	-
RS	4	BG, HR, HU, RO	3	HR, HU, RO	1	BG	0	-	0	-
SE1	3	FI, NO4, SE2	1	SE2	0	-	0	-	2	FI, NO4
SE2	4	NO3, NO4, SE1, SE3	1	SE1	0	-	0	-	3	NO3, NO4, SE3
SE3	5	DK1, FI, NO1, SE2, SE4	0	-	2	FI, SE4	1	DK1	2	NO1, SE2
SE4	5	DE_LU, DK2, LT, PL, SE3	1	DK2	1	SE3	1	LT	3	DE_LU, LT, PL
SEM	1	GB	0	-	1	GB	0	-	0	-
SK	3	CZ, HU, PL	1	CZ	1	HU	1	PL	0	-
SL	3	AT, HR, IT N	2	HR, IT N	1	AT	0	-	0	-

Source: calculated by authors based on ENTSO-E Transparency Platform database of day-ahead prices and scheduled commercial exchanges [17].

Appendix D

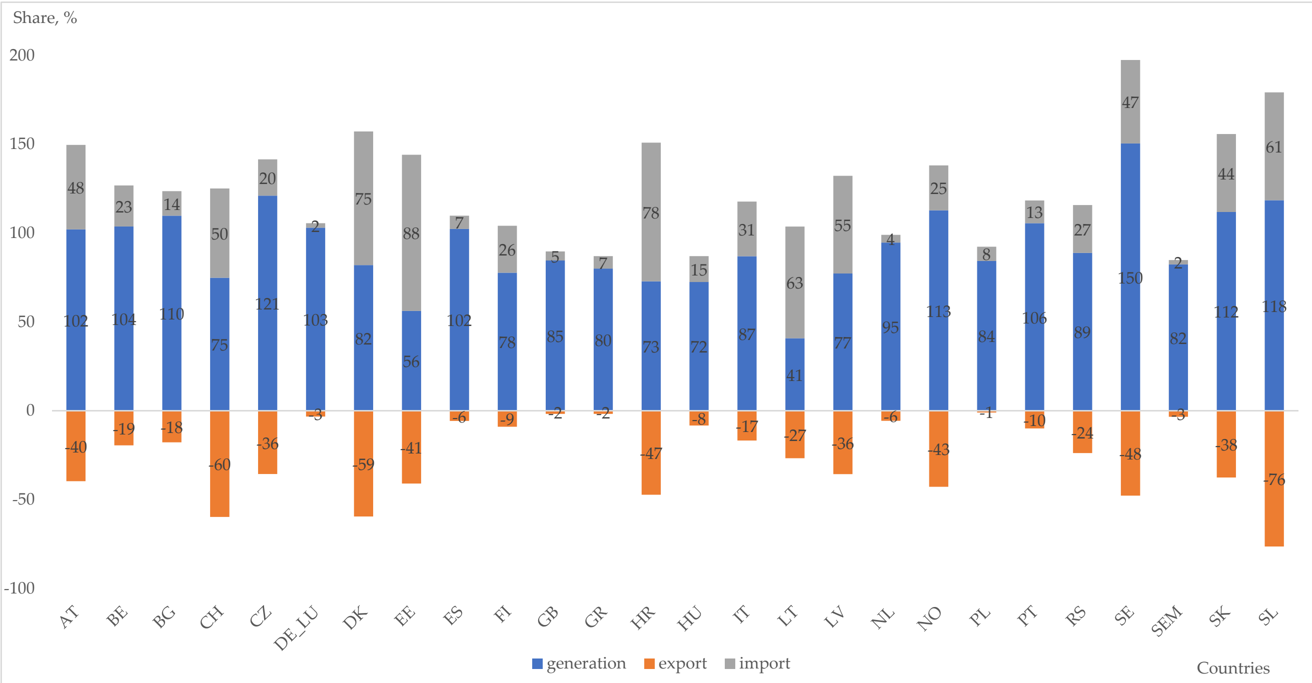

Figure A1. Directions of physical electricity flows in European electricity markets in 2020. Source: calculated by authors based on ENTSO-E Transparency Platform database of cross-border physical flow and actual generation per production type [17].

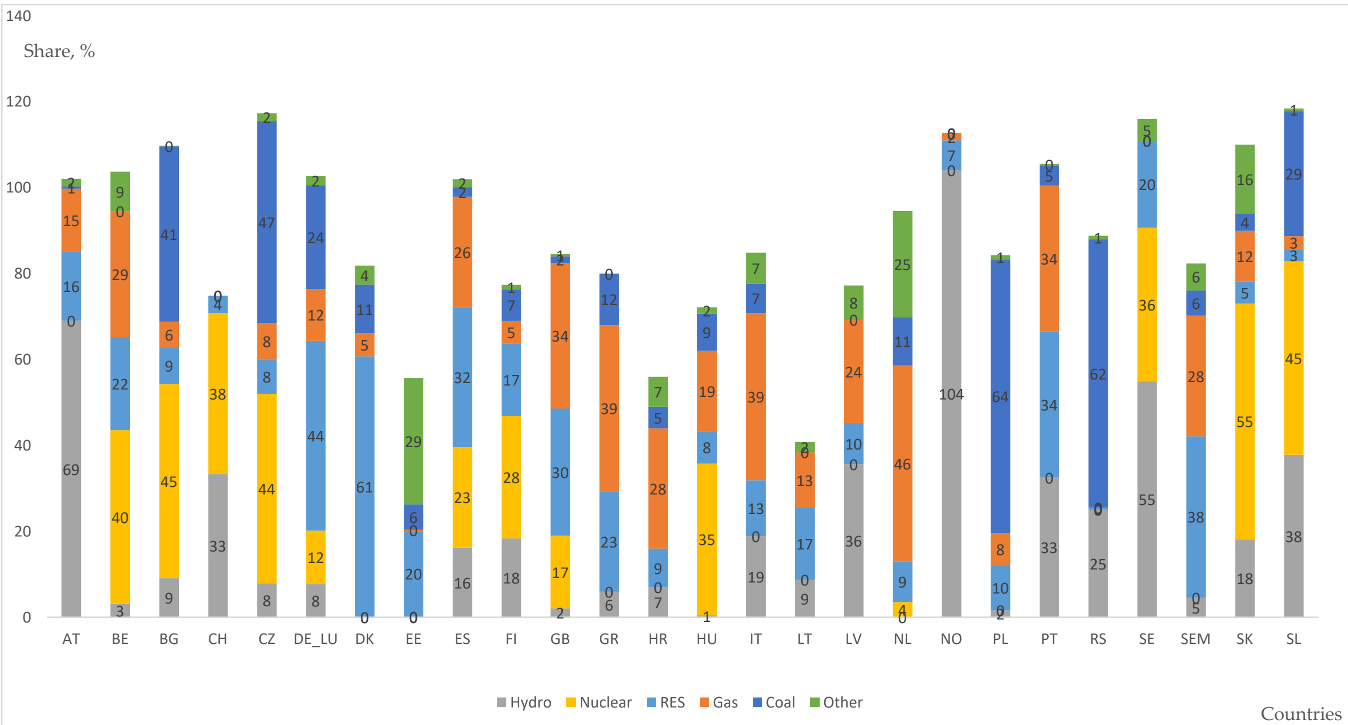

Figure A2. Generation structure of European electricity markets in 2020. Source: calculated by authors based on ENTSO-E Transparency Platform database of actual generation per production type and day-ahead prices [17].

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