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Unraveling European electricity price volatility: The impact of renewables

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ABSTRACT

The transition from fossil fuels to renewable, carbon-free energy is a critical challenge for mitigating climate change, with different European countries adopting diverse approaches to integrating renewable energy sources into their energy systems. Hereby, the intermittent nature and variability of renewable energy generation lead to significant challenges to electricity markets, amplifying supply volatility and market instability. This study examines the determinants of electricity price volatility in European wholesale markets, focusing on the impact of renewable energy sources as well as the influence of fuel prices and electricity demand. Using daily data from thirteen European electricity markets for the period 2015 to 2023, we account for the dynamic development of the energy system and volatile market condition, including the recent shocks induced by the Russia–Ukraine war. By employing country-specific and panel regression models, the findings reveal that conventional power sources, such as nuclear and coal, tend to stabilize electricity markets. In contrast, a higher share of solar power is associated with increased risk. Wind power exhibits mixed effects, with stabilizing impacts in most markets and volatility-enhancing tendencies in Spain, highlighting the role of market-specific dynamics. Additionally, total electricity load as well as the Russia-Ukraine war emerge as significant drivers of market risk.

1. Introduction

The shift from a fossil fuel-dependent global energy system to one centered on renewable, carbon-free resources is among the most critical challenges of our time, as highlighted by Johnson and Oliver [1]. To mitigate the escalating threats of anthropogenic climate change, energy policy plays a central role in steering this transformation. The energy sector, which contributes a significant portion of the EU's total greenhouse gas emissions, must undergo a profound shift by significantly increasing the share of electricity generated from renewable energy sources, such as wind and solar photovoltaics, see European Commission and Directorate-General for Communication [2].

However, the intermittent nature of renewable energy generation, often driven by weather-related fluctuations, introduces significant challenges to electricity markets, which are inherently dynamic and characterized by substantial price volatility, see e.g. Ballester and Furió [3]. In this context, de la Esperanza Mata Pérez et al. [4] note that Poland remains highly skeptical of renewable energy, with widespread perceptions that it is too costly and unstable, thereby posing a potential threat to energy supply security. Unlike most other commodities, electricity cannot yet be economically stored at scale, necessitating real-time balancing of supply and demand, see Biancardi and Staffell [5],Jaeck and Lautier [6]. On the supply side, market stability is influenced by factors such as generation capacity, fuel prices, and the weather-dependent nature of renewable energy, whereby Ortner and Totschnig [7] emphasize that the magnitude of system imbalances is closely linked to the share of variable renewable electricity. On the demand side, weather-dependent consumption patterns, economic activity, and technological developments contribute to market fluctuations. In addition, regulatory interventions, transmission constraints, and geopolitical events further amplify uncertainty. Seasonal mismatches between supply and demand also play a critical role and are expected to increasingly coincide across balancing zones in the future, as noted by Lienhard et al. [8]. In addition, recent global crises underscore the vulnerability of electricity markets to external shocks. The COVID-19 pandemic disrupted both electricity demand and market functioning, while the Russia–Ukraine war triggered a sharp rise in natural gas prices and electricity costs, particularly in gas-dependent countries, see Cevik and Ninomiya [9],Al-Saidi [10]. In this context, Georgescu et al. [11] report evidence for Romania that the association between electricity prices and their key determinants changes markedly from 2021 onward, consistent with a structural shift in market conditions.

In this context, the integration of renewable energy sources into electricity markets additionally induces two countervailing effects on price variability, see Johnson and Oliver [1]. The stochastic merit-order effect reduces c.p. price volatility by shifting the supply curve outward, flattening the relationship between supply and demand, and

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thus suppressing short-term price fluctuations. Conversely, the intermittency effect amplifies volatility due to the unpredictable nature of renewable generation, causing frequent and stochastic shifts in the supply curve. Consequently, a deep understanding of the underlying drivers of electricity price volatility, particularly the transformative impact of renewable energy generation, is essential for designing effective markets, developing robust risk management strategies, and crafting sound, forward-looking policies.

However, empirical work to date has predominantly focused on the merit-order effect of renewables on wholesale electricity price levels, whereas their impact on price volatility has received far less systematic attention. For a concise overview of the existing studies, including their country coverage, methodological approaches, data frequency, and sample periods, see Table 1. The merit-order effect of wind and solar power has been documented for several individual European markets, including Germany, Greece, Italy, Spain, and the UK, for example in [3,12–21]. In contrast, Bâra et al. [22] report that higher renewable penetration in Romania's electricity system coincides with higher intraday prices. These studies, however, are almost exclusively country-specific, whereas Cevik and Ninomiya [9] likewise find in a broader cross-country setting that renewable generation exerts downward pressure on wholesale prices using a panel of 24 European countries. A related literature strand examines volatility spillovers across European power markets, see, for example, Cevik and Zhao [23], Ma et al. [24], Schischke and Rathgeber [25], Sikorska-Pastuszka and Papiez [26], and Xiao et al. [27]. These contributions provide important evidence on how shocks propagate between markets, but do not systematically analyze how the generation mix and other fundamentals within each market shape volatility.

Against this backdrop, Johnson and Oliver [1] emphasize that the impact of renewable energy on electricity price volatility itself remains underexplored despite its critical importance. Subsequently, Božić et al. [30] contribute an initial descriptive analysis of price volatility in several European electricity markets, offering valuable preliminary findings. They reveal substantial differences between European electricity markets. In particular, the volatility is higher in newer Southeast European markets, such as Bulgaria and Romania, compared to more established markets like Greece and Switzerland, which exhibit the lowest levels of volatility. Nonetheless, the study does not delve into the underlying drivers of the volatility.

A growing body of empirical work has begun to address the impact of renewable generation on electricity price volatility itself, but results remain mixed and are often based on single-country analyses. In particular, Ballester and Furió [3] identify a positive relationship between renewable generation and daily price volatility in Spain. Similarly, Brancucci Martinez-Anido et al. [12] and Green and Vasilakos [32] confirm the volatility-enhancing effect of wind power in the UK market. Additionally, Pereira da Silva and Horta [34] and Ketterer [16] report a positive association between wind power and daily price volatility in the Iberian region and Germany, respectively. Moreover, Bâra et al. [28] reveal that renewable generation is associated with more unpredictable market dynamics and higher volatility in Romania's intraday electricity prices. However, the findings of Rintamäki et al. [35] are more nuanced. While they also conclude that wind power increases price volatility in Germany, their results show a reduction in volatility in Denmark. Furthermore, their analysis highlights that solar power contributes to reducing price volatility.

Other studies also point to more mixed or even neutral effects. Hereby, Khoshrou et al. [33] find that the increasing integration of renewable energy sources did not lead to greater volatility in the German day-ahead electricity market. Moreover, Maciejowska [17], Wozabal et al. [36], and Maniatis and Milonas [18] reveal for Germany and Greece that the volatility impact of renewables depends on demand conditions and market context rather than being uniform across systems. Furthermore, Cevik and Ninomiya [9] report mixed evidence on the relationship between renewable generation and electricity price volatility across 24 European markets, employing panel regression techniques. While their linear panel models do not reveal a significant overall effect, their quantile regression analysis suggests that renewables may exert a volatility-reducing influence, particularly in the upper tails of the distribution. In contrast, Johnson and Oliver [1] identify an overall positive impact of wind and solar power on electricity price volatility in their panel analysis spanning 19 countries. This conclusion is corroborated by Clò et al. [13] and Sapio [20] for Italy, as well as by Figueiredo and da Silva [15] for the Iberian region.

Taken together, these studies all consider the effect of renewables (wind, solar, or both) on electricity price volatility, but they differ substantially in geographic scope (typically single-country markets), sample period, and methodological approach. Most rely on linear regression or GARCH-type models [3,13,15,16,18,34–36], sometimes extended to quantile regressions [17,20], while others use production cost modeling [12], equilibrium modeling based on future scenarios [32], or wavelet decomposition [33]. With the exception of Rintamäki et al. [35], which compares Germany and Denmark, the majority of these contributions are single-country or single-region studies and thus cannot systematically exploit cross-country differences in generation mixes and market design. The panel studies by Cevik and Ninomiya [9] and Johnson and Oliver [1] cover a broader set of European markets, but they primarily report average effects for Europe as a whole and do not examine country-specific heterogeneity in the volatility impact of renewables.

While these studies mainly focus on the renewables–volatility nexus, other determinants also matter. For example, Chen and Bunn [31] explored the fundamental and behavioral drivers of volatility in the UK market, finding that factors such as economic fundamentals, strategic behaviors, and market design significantly influence fluctuations. Moreover, Birkeland et al. [29] detect gas and coal prices affect the volatility in the Dutch electricity prices. In addition, Zakeri et al. [37] emphasize that natural gas has become the primary electricity price setter in Europe as a result of the energy transition. Consequently, European electricity markets are highly vulnerable to geopolitical risks related to gas supply, natural gas price volatility, and economic risks stemming from currency exchange fluctuations. This broader perspective highlights the need to account for multiple drivers beyond renewable energy integration.

Although existing contributions offer valuable insights into the link between renewables and electricity price volatility, many remain confined to single-country analyses; even when additional drivers such as fuel prices or demand are included, their findings are difficult to generalize because national energy systems are relatively stable over time yet differ strongly across countries. Broader European studies, where available, are based on pre-2021 data and therefore do not fully reflect recent developments, such as the Russia–Ukraine war or post-pandemic adjustments. This lack of cross-regional analysis raises questions about the external validity of existing findings in a European context, where the technology mix for electricity generation varies widely due to differences in policy priorities, historical policy decisions, and resource availability, see Fig. 1. For instance, France relies predominantly on nuclear power for electricity generation, while Germany has shifted away from nuclear and coal in favor of renewables, particularly wind and solar. In contrast, Poland remains heavily reliant on coal, whereas Norway predominantly uses hydropower, leveraging its abundant water resources. These diverse generation profiles underscore the need for research that goes beyond single-country analyses and allows a comparative assessment of how different generation technologies, market conditions, and regional characteristics jointly shape price volatility. Addressing these gaps is essential to better understand the multifaceted nature of electricity price volatility in the context of a rapidly evolving energy landscape.

This study contributes to the literature by offering a comprehensive analysis of the determinants of electricity price volatility across thirteen European countries, with a particular focus on the role of renewable energy sources. Using both country-specific and panel regression analyses with daily data over the period 2015–2023, we exploit recent market developments, including the COVID-19 pandemic and the Russia–Ukraine energy crisis.

Table 1
Literature overview.

Author	Country	Methodology	Frequency	Start	End
Al-Saidi [10]		Discussion of energy security			
Ballester and Furió [3]	Spain	Pearson test, regression analysis	Daily	2001	2013
Bâra et al. [22]	Romania	ARDL model	Hourly	2024	2024
Bâra et al. [28]	Romania	Dual approach	Hourly	2024	2025
Biancardi and Staffell [5]		Interviews			
Birkeland et al. [29]	The Netherlands	linear regression and random forest models	Daily	2020	2023
Božić et al. [30]	15 European electricity markets	Correlation analysis	Hourly	2016	2019
Brancucci Martinez-Anido et al. [12]	UK	Production cost model	Hourly	2010	2010
Cevik and Ninomiya [9]	24 European electricity markets	Panel	Daily	2014	2021
Cevik and Zhao [23]	24 European electricity markets	Volatility spillovers	15-minutes	2014	2024
Chen and Bunn [31]	UK	Smooth transition regression model	half-hourly	2005	2006
Clò et al. [13]	Italy	Regression analysis and EGARCH models	Daily	2005	2013
Dillig et al. [14]	Germany	Market model	Hourly	2011	2013
Figueiredo and da Silva [15]	Iberian region	AR-GARCH	Daily	2008	2017
Georgescu et al. [11]	Romania	PCA, continuous wavelet transformation, Granger causality	Daily	2009	2022
Green and Vasilakos [32]	UK	Numerical supply function equilibrium model	Hourly	1993	2005
Jaeck and Lautier [6]	German, Nordic, Australian, and US markets	Tests for the Samuelson effect	Daily	2008	2014
Johnson and Oliver [1]	19 European electricity markets	Panel	Quarterly	2000	2011
Ketterer [16]	Germany	AR-GARCH	Daily	2006	2012
Khoshrou et al. [33]	Germany	Wavelet decomposition	Hourly	2006	2016
Lienhard et al. [8]		Scenario analysis			
Maciejowska [17]	Germany	Quantile regression model	Daily	2015	2008
Ma et al. [24]	12 European electricity markets	Volatility spillovers	Daily	2009	2020
Maniatis and Milonas [18]	Greece	AR-GARCH	Daily	2012	2018
de la Esperanza Mata Pérez et al. [4]		Review of EU energy security			
Ortner and Totschnig [7]	EU Member States and in addition Norway, Switzerland, the Western Balkan countries, North Africa and Turkey.	Market model High Resolution Power System			
Paraschiv et al. [19]	Germany	Dynamic fundamental model	Hourly	2010	2013
Pereira da Silva and Horta [34]	Iberian region	Regression analysis and EGARCH models, AR-GARCH	Daily	2010	2015
Rintamäki et al. [35]	Germany, Denmark	Autoregressive moving average model	Daily	2010	2014
Sapio [20]	Italy	Quantile regression analysis	Daily	2006	2015
Schischke and Rathgeber [25]	9 European electricity markets	Volatility spillovers	Daily	2015	2023
Sikorska-Pastuszka and Papiez [26]	26 European electricity markets	Volatility spillovers	Daily	2007	2022
Wozabal et al. [36]	Germany	Regression model	Daily	2007	2013
Würzburg et al. [21]	Austrian–German region	Regression model	Daily	2010	2012
Xiao et al. [27]	11 European electricity markets	Volatility spillovers	Daily	2013	2017
Zakeri et al. [37]	29 European electricity markets	Price-generation differential method	Hourly	2015	2021

This table summarizes key studies in the literature, indicating for each the countries examined, the methodological approach, the data frequency, and the start and end of the sample period.

Against this background, the paper pursues the following research objectives and contributions:

- We quantify how different generation technologies (nuclear, coal, gas, solar, wind, and other renewables and non-renewables) affect realized electricity price volatility across thirteen European day-ahead markets, and assess to what extent these effects are common across countries or driven by market-specific characteristics.
- We examine the joint role of electricity demand (both domestic load and aggregate European generation), fuel and carbon prices, and broader economic conditions in shaping volatility, alongside the generation mix, thereby addressing omitted variable bias.
- We identify and quantify the impact of recent major geopolitical shocks, the COVID-19 pandemic and the Russia–Ukraine war, on electricity price volatility.
- We compare country-specific regression results with panel estimates to distinguish country-level idiosyncrasies from common European drivers of volatility.

Relative to existing multi-country studies, this paper has three key strengths. First, the 2015–2023 sample period covers major structural breaks in European electricity markets, including the COVID-19 pandemic and the Russia–Ukraine energy crisis, ensuring that the analysis captures the most recent market disruptions. Second, the paper jointly examines the generation mix, electricity demand, fuel and carbon prices, financial conditions, and geopolitical shocks within a unified empirical framework. Third, by combining country-specific regressions with random-effects panel models, the analysis improves cross-market comparability while preserving country-level heterogeneity.

The empirical results reveal that conventional energy sources, such as nuclear and coal, tend to stabilize electricity markets, whereas a higher share of solar power is associated with increased volatility in European electricity markets. In contrast, wind power exhibits mixed effects: while a higher share of wind power increases risks in Spain, consistent with previous findings in the literature, it has a stabilizing effect in most other European electricity markets, highlighting the importance of market-specific dynamics. The study also underscores the significant impact of electricity demand, proxied by total electricity generation, showing that higher demand amplifies market risks. Moreover, the Russia–Ukraine war markedly intensified electricity price volatility, and the COVID-19 pandemic also had volatility-increasing effects in most European electricity markets.

By elucidating these dynamics, this research deepens the understanding of electricity price volatility and its drivers, with direct implications for energy and climate policy. The finding that conventional technologies such as nuclear and coal tend to stabilize prices, while higher solar penetration is associated with increased volatility, underscores the importance of complementary flexibility mechanisms, including storage, demand response, and dispatchable backup capacity, to accompany further solar deployment. The heterogeneous effects of wind power across countries highlight that market design and system characteristics play a critical role, suggesting that renewable support schemes and balancing arrangements should be tailored to national conditions rather than uniformly applied. Moreover, the strong volatility-amplifying role of electricity demand points to the relevance of demand-side participation and dynamic pricing as tools to mitigate market risks during high-load periods. Finally, the pronounced volatility increases observed during the COVID-19 pandemic and the Russia–Ukraine war emphasize the need for robust cross-border grid integration and effective hedging instruments, enabling market participants to manage risk and enhancing the resilience of electricity markets during periods of severe external shocks. In doing so, the paper contributes to the development of more resilient electricity markets capable of supporting the transition to a sustainable, low-carbon European energy system.

The remainder of this paper is organized as follows: Section 2 provides a concise overview of the methodological framework employed. Sections 3 and 4 detail the empirical analysis and present the findings, respectively, while Section 5 offers the concluding remarks.

2. Methodology

Overall, we employ linear regression models to examine the main drivers of electricity price volatility in European electricity markets. Hereby, we adopt a linear specification because we aim to quantify average marginal effects of fundamentals on (log) realized volatility, allowing for a direct and transparent interpretation of coefficients, in line with the previous empirical literature on electricity price volatility, see Table 1. The set of explanatory variables includes generation technology shares, measures of electricity demand, and macroeconomic and energy price variables, reflecting their potential influence on electricity market dynamics, see Section 3. We first estimate country-specific regressions and subsequently panel regressions.

First, we consider country-specific individual linear regression models. Those allow us to capture the unique characteristics and dynamics of each country's electricity market. In particular, this analysis provides detailed insights into how the share of renewables and exogenous variables impact volatility at the national level. Moreover, it helps to identify heterogeneity across countries in terms of the relationship between independent variables and volatility. The linear regression model is specified as follows:

$$v_{i,t} = \beta_{0,i} + \beta_{1,i} X_{1,i,t} + \beta_{2,i} X_{2,i,t} + \cdots + \beta_{K,i} X_{K,i,t} + \varepsilon_{i,t} \tag{1}$$

where $v_{i,t}$ represents the volatility of the electricity price of country $i = 1, 2, \ldots, N$ at time $t = 1, 2, \ldots, T$. The K independent variables $X_{1,i,t}, X_{2,i,t}, \ldots, X_{K,i,t}$ include the share of renewable energy, macroeconomic factors, and energy prices, see Section 3, whereby the parameters $\beta_{1,i}, \beta_{2,i}, \ldots, \beta_{K,i}$ capture the corresponding impact of these variables on the volatility. The error term $\varepsilon_{i,t}$ is assumed to be independent and identically distributed with zero mean and variance σ_i^2, thus $\varepsilon_{i,t} \sim iid(0, \sigma_i^2)$. The country-specific linear regression models are estimated using Ordinary Least Squares (OLS) with Newey–West standard errors to address potential heteroscedasticity and autocorrelation.

Second, we employ panel regression models to examine whether the findings from country-specific regressions hold at a broader level. Those exploit cross-country and time-series variations, enhancing statistical power and robustness. In particular, the panel regression accounts for unobserved heterogeneity through random effects,[1] capturing differences in country-specific characteristics and allowing for time-varying volatility differences between countries. This approach is also economically justified, as persistent fixed effects would imply that cross-country differences in volatility remain constant over time. However, given the increasing integration of European electricity markets, evolving energy policies, and structural shifts, such as renewable expansion and market coupling, volatility patterns are likely to change over time, making the random effects model a more appropriate choice. This is inter alia underlined by Schischke and Rathgeber [25], as cross-border volatility spillovers evolve over time. Overall, it is useful for identifying broader, generalized trends and the impact of common factors on volatility across countries. Hereby, the panel regression model is defined as:

$$v_{i,t} = \beta_0 + \beta_1 X_{1,i,t} + \beta_2 X_{2,i,t} + \cdots + \beta_K X_{K,i,t} + u_i + \varepsilon_{i,t}, \tag{2}$$

where $v_{i,t}$ represents the volatility of country $i = 1, 2, \ldots, N$, The K independent variables $X_{1,i,t}, X_{2,i,t}, \ldots, X_{K,i,t}$ can be country-specific and the parameters $\beta_1, \beta_2, \ldots, \beta_K$ capture the general impact of these variables on the volatility. Further, u_i denotes the random individual specific effect which is uncorrelated with the country-specific regressors, while $\varepsilon_{i,t}$ denotes the error term. To address potential heteroscedasticity and autocorrelation, we utilize robust standard errors as proposed by Amemiya [38].

3. Data

This study aims to examine the factors driving electricity price volatility in European wholesale spot electricity markets. To this end, an hourly price dataset covering thirteen European day-ahead electricity markets is used to derive realized intraday volatility series for the period from January 1, 2015, to December 31, 2023. The dataset, sourced from ENTSO-E Transparency Platform [39], includes electricity spot prices that have been standardized to EUR/MWh and converted to a common time zone, with all observations aligned to Coordinated Universal Time (UTC) to ensure cross-country comparability.[2] This analysis focuses on thirteen electricity markets across Northern, Western, Southern, and Central-Eastern Europe. In particular, we analyze the electricity price volatility in Switzerland, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Hungary, Italy, Norway, Poland, and Sweden, which are operated by seven key power exchanges: EPEX, HEnEx, HUPX, Nord Pool, OMEL, GME and TGE.[3]

In line with the literature, e.g. Johnson and Oliver [1],Rintamäki et al. [35], we calculate the realized volatilities per country $i = 1, 2, \ldots, N$ which are defined as the summation of the squared price changes over day $t = 1, 2, \ldots, T$:

$$RV_{i,t} = \sqrt{\sum_{\mathfrak{h}=1}^{24} (price_{i,t,\mathfrak{h}} - price_{i,t,\mathfrak{h}-1})^2}, \tag{3}$$

[1] The Hausman test prefers in each case the panel regression with random effects over the model with fixed effects, therefore, we only report the results of the random effects model in this study.

[2] Following Ma et al. [24] who examine the determinants of volatility spillovers, weekend price data is excluded to focus on periods of higher electricity usage and to facilitate the incorporation of financial variables in the regression analysis.

[3] In panel regression models, the inclusion of numerous highly correlated markets can reduce statistical power and bias the estimation of common effects due to multicollinearity. For this reason, it was not feasible to incorporate additional countries from Northern, Western, and Southern Europe into our analysis, given the high degree of interconnectivity and similar market structures across certain regions. Specifically, Estonia, Latvia, and Lithuania form the integrated Baltic electricity market, while Spain and Portugal operate within the jointly managed MIBEL (Mercado Ibérico de Electricidade). Romania and Bulgaria also maintain strong trading relationships with each other and with Greece. Similarly, Belgium, Switzerland, Germany, Luxembourg, Austria, and the Netherlands primarily trade via the EPEX SPOT platform, further increasing market integration. These shared market systems lead to electricity price volatility correlations exceeding 90%, making it statistically impractical to include all of these countries in the analysis. In addition, Iceland, Ireland, the United Kingdom, and countries participating in the Southeast Europe Power Exchange (SEEPEX) were excluded due to data availability constraints.

where $price_{i,t,\mathfrak{h}}$ with $\mathfrak{h} = 1, 2, \ldots, 24$, are hourly electricity spot prices on day t in country $i = 1, 2, \ldots, N$.[4] To ensure the robustness of our results, we also estimate the volatility by the intraday price range, following the literature on volatility spillover effects in European electricity markets, see e.g. Ma et al. [24],Sikorska-Pastuszka and Papiez [26]. Moreover, following Do et al. [41], we address the non-negativity constraint in volatility modeling by applying a natural logarithm transformation to the volatility measure, which both ensures strictly positive values and enhances the stationarity of the series.

The explanatory variables are designed to capture both supply- and demand-side drivers of electricity price volatility, consistent with the fundamental market dynamics of real-time supply–demand balancing. They include the generation mix by technology, economic activity, energy market indicators, and extraordinary events, reflecting how generation capacity, fuel prices, intermittent renewables, weather-dependent consumption, and geopolitical disruptions shape market risks. Given that our model focuses on intraday volatility, we can reasonably treat the explanatory variables as exogenous, since short-term price fluctuations are unlikely to feed back into fundamentals such as daily demand or the generation mix. In particular, Clò et al. [13] emphasize for the daily frequency that electricity consumption is largely price-insensitive and the production of renewable energy sources (RES) is driven by weather conditions and cannot be strategically adjusted in response to price dynamics.

Generation data for nuclear, weather-dependent renewables such as solar and wind, other renewables (biomass, geothermal, hydro), as well as non-renewables such as gas, coal, and other non-renewables (oil, waste) were obtained at hourly frequency from ENTSO-E Transparency Platform [39] and aggregated to daily total generation. Technology shares were then computed as the proportion of daily generation from each technology relative to total daily generation.[5]

To control for electricity demand, the total daily load per country is also included. Moreover, we incorporate the total electricity generation of the considered countries, recognizing that markets are interconnected through cross-border electricity trading. The demand for electricity in neighboring countries can influence domestic market dynamics, potentially impacting price volatility within the domestic market.

Additionally, fundamental energy price drivers such as oil, natural gas, and coal prices are included. Brent oil futures, TTF natural gas futures, and API2 Rotterdam coal futures, as provided by Datastream [42], are used as proxies for these fuels. To address term structure effects, artificial constant maturity futures prices are constructed for each energy source. The EU Allowance (EUA) price, which reflects the marginal cost of coal-based electricity generation, is incorporated using the 365-day constant maturity price for December futures contracts, as in Hagfors et al. [43]. Broader economic conditions are accounted for through the inclusion of the Stoxx Europe 600 index, which serves as a proxy for overall investor sentiment and the economic environment in Europe. Finally, to capture the impact of extraordinary events, two dummy variables are included: one indicating the period of the COVID-19 pandemic (March 2020 to June 2021) and another for the period following the onset of the Russia–Ukraine war (from February 24, 2022, onward). These dummies account for potential structural breaks and the heightened market uncertainty associated with these crises, allowing their distinct impacts on electricity price volatility to be explicitly captured. By including these variables, the dataset provides a comprehensive foundation for analyzing the drivers of electricity price volatility in European wholesale markets.

Descriptive statistics for the variables are presented in Tables 2 and 5. Since all exogenous variables, technology shares, total (domestic and aggregate European) load, the Stoxx Europe 600 index, and fuel and emission prices, are non-stationary in levels, we work with their daily logarithmic returns. This transformation ensures stationarity and helps to avoid spurious regression results. A detailed description of the data preprocessing steps (time-zone standardization, aggregation from hourly to daily frequency, outlier treatment, and construction of log-volatility and returns) is provided in Appendix A.1. The descriptive statistics highlight substantial variability in electricity price volatility across countries, with markets in the Nord Pool region exhibiting higher levels of volatility compared to less interconnected markets like Italy. Moreover, we observe a noticeable increase in electricity price volatility across all markets in 2022, coinciding with the onset of the Russia–Ukraine war, see Fig. 2. Most explanatory variables display high kurtosis, indicating fat-tailed distributions, with solar power shares in Finland and Sweden showing extreme kurtosis due to their negligible levels until recent years.

4. Empirical results

The integration of renewable energy sources into electricity markets raises critical concerns about market stability, see Ballester and Furió [3]. As noted by Johnson and Oliver [1], the integration of renewable energy sources introduces two countervailing effects on electricity price variability: the stochastic merit-order effect, which tends to reduce volatility by shifting the supply curve outward and flattening the price response to demand fluctuations; and the intermittency effect, which increases volatility due to the unpredictable and variable nature of renewable generation, leading to frequent and erratic shifts in the supply curve. Therefore, this section examines how the growing share of renewable energy influences electricity price volatility across European markets. Using regression techniques, we analyze the determinants of volatility in electricity prices, with a particular focus on the shares of various generation technologies. These technologies are categorized into nuclear, solar, wind, other renewables (including biomass, geothermal, hydro, and other renewable sources), gas, coal, and other non-renewables (such as oil, waste, and other sources). The model incorporates domestic and total European electricity load, alongside key price drivers such as the prices of Brent oil, natural gas, coal, and carbon emissions, following Hagfors et al. [43], as well as dummy variables for the COVID-19 pandemic (COVID) and the Russia–Ukraine war (Ukraine). Additionally, macroeconomic conditions are captured through the inclusion of the Stoxx Europe 660 index to account for broader economic activity and investor sentiment across Europe.

The country-specific regression results, summarized in Table 3 and detailed in Table 6,[6] reveal significant differences across European electricity markets, highlighting the diverse impact of load and technology shares on price volatility, whereas neither the fuel prices, the carbon emission price nor the economic activity, represented by the Stoxx Europe 660 index, significantly affect the electricity volatility of any country.

Electricity load emerges as a crucial determinant of volatility, with an increase in electricity demand generally leading to higher market risks. This positive relationship is evident in most countries, though it

[4] In line with Apergis et al. [40] and Ma et al. [24], we calculate volatility based on raw prices rather than logarithmic transformations, as negative electricity prices are observed in the dataset.

[5] The composition of "other renewables" differs across countries. In Denmark this category consists almost entirely of biomass, whereas in Switzerland, Greece, Norway, and Sweden it is exclusively hydro. In Estonia, "other renewables" are dominated by biomass, as hydro plays only a minor role. In Spain and France, by contrast, the category mainly reflects hydro, with very small biomass contributions. Germany, Finland, Hungary, and Poland report "other renewables" as a combination of hydro and biomass, with hydro generally accounting for the larger share; in Poland, however, the overall contribution of "other renewables" to total generation remains small. Geothermal generation is negligible or absent in all sample countries.

[6] Due to stationarity issues, we use logarithmic differences for our exogenous variables, while the volatilities are logarithmized. This results in different value ranges, which explains the high intercept values observed.

Table 2
Descriptive statistics for the log volatility per country.

	Min.	Median	Mean	Max.	St.Dev.	Skewness	Kurtosis	ADF
Denmark	0.17	3.22	3.32	6.18	0.97	0.13	3.16	−4.50**
Estonia	0.76	3.58	3.74	7.00	1.00	0.39	2.75	−3.43**
Finland	0.76	3.44	3.53	7.00	0.96	0.37	3.10	−4.59**
France	1.97	3.27	3.49	6.11	0.76	0.88	3.07	−2.18*
Germany	2.06	3.26	3.54	7.13	0.85	1.18	3.95	−2.39*
Greece	−0.15	3.38	3.48	6.51	1.05	0.25	2.48	−3.77**
Hungary	2.21	3.43	3.67	6.47	0.76	0.87	2.93	−2.19*
Italy	1.92	3.30	3.48	5.84	0.71	0.82	3.10	−2.07*
Norway	−2.40	1.75	1.94	5.87	1.23	0.26	3.11	−6.92**
Poland	1.76	3.11	3.33	6.19	0.78	0.96	3.45	−3.19**
Spain	0.91	2.85	3.01	5.44	0.79	0.52	2.66	−2.48*
Sweden	−0.14	2.82	2.97	6.26	1.12	0.37	2.68	−5.28**
Switzerland	1.28	2.94	3.16	5.58	0.74	0.88	3.19	−2.24*

This table presents the minimum, median, mean, maximum, standard deviation, skewness, and kurtosis of the logarithmized volatility, calculated as the daily realized volatility for each country. Moreover, the test statistics of the Augmented Dickey Fuller (ADF) test are reported, whereby ** (*) indicate significance at the 1% (5%) level.

is not statistically significant in Germany, Spain, Greece, and Hungary. For most countries, volatility is primarily driven by the country-specific load, indicating that an increased local electricity consumption intensifies the challenge of balancing supply and demand and thereby amplifies price fluctuations, consistent with the inverse leverage effect, where rising demand and prices are associated with increased volatility, see Chen and Mu [44]. In addition, in Estonia, Finland, Norway, and Sweden, which are part of the highly interconnected Nord Pool market, the aggregated European load also has a significant impact on volatility. This suggests that in these strongly integrated markets, overall European demand, transmitted through cross-border electricity flows, significantly influences price variability.

Similarly, both the COVID-19 pandemic and the Russia–Ukraine war heightened volatility in European electricity markets. The Russia–Ukraine war, with its associated surge in gas prices and heightened uncertainty, significantly increased electricity price volatility across all European markets under study, consistent with the inverse leverage effect in electricity markets, where higher prices coincide with elevated volatility due to supply constraints and market stress, see Chen and Mu [44]. In contrast, the COVID-19 pandemic, with widespread lockdowns and a highly uncertain economic environment, significantly affected the volatility in Nordic, Baltic, Southern and Central-Eastern European markets, while we do not observe any significant effect for the large core continental markets. Hereby, the COVID-19 pandemic led to higher volatility in Denmark, Estonia, Finland, Greece, and Sweden. Interestingly, Hungary, Italy, and Norway experienced lower volatility during the pandemic period, potentially because reduced electricity demand during lockdowns made it easier to maintain supply–demand balance in these markets. By contrast, no significant effect is found for the large core continental markets (France, Germany, Switzerland, Spain and Poland), where deeper market integration and more diversified generation portfolios may help to absorb such shocks.

The composition of generation technologies further shapes market dynamics. The results indicate that nuclear and coal power have a stabilizing effect, reducing volatility in Germany, France, Spain, and Estonia. This highlights the ability of stable conventional power sources to mitigate risks in electricity markets. In contrast, the impact of gas-fired power generation is mixed. Countries with a higher reliance on gas, such as Greece, Hungary, and Italy, exhibit reduced volatility when the share of gas power increases, whereas volatility rises in countries like Estonia, Finland, and Denmark, where gas accounts for a smaller proportion of total generation, see Fig. 1. These differences may reflect the greater operational flexibility in countries with substantial gas capacity, where gas plants can be quickly adjusted to buffer fluctuations and balance supply and demand effectively. In countries with limited gas capacity, however, the smaller and less integrated gas fleet may be insufficient to mitigate volatility during periods of high demand or low renewable output.

Non-renewable energy sources, including oil and waste, also demonstrate varying effects on volatility. In Finland and Sweden, where the share of non-renewables is small but more stable compared to other countries, an increase in non-renewable generation is associated with heightened volatility. Conversely, in countries with a very low average share, such as Denmark, Norway, Spain, and Greece, increasing the share of non-renewables appears to stabilize electricity prices, possibly due to the availability of underutilized capacity, see Fig. 1. Interestingly, in Spain, however, higher oil prices are associated with increased electricity price volatility despite oil's low average share in generation, likely reflecting its strong correlation with other key energy inputs, such as natural gas, and its role as an indicator of broader economic conditions and energy market sentiment.

Solar and wind power exhibit contrasting effects on market stability. An increase in the share of solar power is associated with higher volatility in Germany and Spain, likely due to the inherently intermittent and weather-dependent nature of photovoltaic generation, which exacerbates electricity price fluctuations. In contrast, wind power appears to have a stabilizing effect in several countries, including Switzerland, Germany, Estonia, Italy, and Sweden. Hereby, the Central European and Nordic countries benefit from strong interconnections with neighboring markets, which enable excess wind power to be exported during periods of high supply, thereby dampening local price volatility. However,in Spain, a higher share of wind power is associated with increased volatility, likely due to limited interconnection capacity and a reduced ability to balance fluctuations through cross-border electricity flows.

The impact of other renewable energy sources, including hydro, geothermal, and biomass, exhibits considerable variation across markets. In Estonia, where "other renewables" consist almost exclusively of biomass and account for only a small average share of total electricity generation, the results indicate a stabilizing effect on market volatility. Conversely, in countries with a more substantial reliance on renewables, such as Finland, France, Germany, Spain, and Greece, where the "other renewables" category is dominated by hydro power and biomass plays only a secondary role, higher shares of renewable energy are associated with increased volatility. For example, in Finland, where renewables (predominantly hydro) account for over one-third of total electricity generation, the risks are intensified by the inherent variability and non-continuous availability of renewable sources, which make it more challenging to maintain a stable balance between supply and demand.

Interestingly, the case of Norway presents a stark contrast. Despite its reliance on hydro power for over 90% of total electricity generation on average, see Fig. 1, the share of renewables does not significantly influence market volatility. Instead, electricity demand emerges as the primary driver of volatility, underscoring the unique market dynamics shaped by Norway's extensive reliance on stable hydroelectric capacity

Table 3
Country-specific determinants of electricity price volatility.

	DK	EE	FI	FR	DE	GR	HU	IT	NO	PL	ES	SE	CH
(Intercept)	+	+	+	+	+	+	+	+	+	+	+	+	+
Other non-renewables	–		+			–			–	+	–	+	
Coal		–	+								–		
Gas	+		+	–		–	–	–			+		
Nuclear				–	–								–
Other renewables		–	+	+	+	+					+		
Solar					+						+		
Wind		–		–	–			–		–	+	–	–
EUA													
Gas price													
Oil price											+		
Coal price													
Country-specific load	+		+	+				+	+	+		+	+
Total load		+	+						+			+	
Stoxx		–								–			
COVID	+	+	+			+	–	–	–			+	
Ukraine	+	+	+	+	+	+	+	+	+	+	+	+	+

The table reports OLS regression results for country-specific electricity price volatility, estimated with Newey–West standard errors to account for heteroskedasticity and autocorrelation, for Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Italy (IT), Norway (NO), Poland (PL), Spain (ES), Sweden (SE), and Switzerland (CH). A "+" ("–") denotes a statistically significant positive (negative) effect of the corresponding explanatory variable on volatility.

with a relatively constant water flow, which ensures a more predictable and controllable supply compared to other renewable sources.

Overall, the findings emphasize the stabilizing role of conventional power sources, such as nuclear and coal, while highlighting the potential of renewables, particularly solar power, to increase market volatility. These results align with prior studies, such as Ballester and Furió [3], Johnson and Oliver [1], Clò et al. [13], Sapio [20], and Figueiredo and da Silva [15], who also empirically confirm the intermittency effect. However, in case of wind, we observe the stochastic merit-order effect outweighs the intermittency effect in most countries. Hereby, the observed stabilizing effect of wind power contrasts with much of the existing literature, which often associates wind power with heightened volatility, see e.g., Ketterer [16],Green and Vasilakos [32],Pereira da Silva and Horta [34]. Notably, Rintamäki et al. [35] report similar stabilizing effects of wind power in the Danish electricity market, suggesting that the influence of wind power may depend on the specific characteristics of national energy systems and their integration of renewable resources.

To further validate the findings from the country-specific regressions, we employ a panel regression model with random effects.[7] This approach leverages both cross-country and time-series variations, enhancing statistical power and robustness. The results of this analysis are presented in Table 4.

The panel regression results largely align with the findings from the country-specific regressions while providing additional valuable insights. Notably, the gas price and the Stoxx Europe 600 index emerge as significant determinants of electricity price volatility, highlighting the importance of input costs and broader economic activity in shaping market risks. Higher gas prices are associated with increased volatility, reflecting both the higher costs of generation and the resulting uncertainty. In contrast, a higher Stoxx Europe 600 index, as a proxy for stronger economic activity and higher electricity demand, appears to dampen volatility, consistent with the inverse leverage effect. Interestingly, the influence of the Stoxx index becomes apparent only in the aggregated panel results and not in the country-level regressions, suggesting that this relationship manifests more clearly at the European market level.

Furthermore, total electricity load is strongly associated with increased volatility, suggesting that rising demand amplifies market instability across European markets. Interestingly, the impact of total load on volatility is considerably more pronounced than that of country-specific loads, highlighting the interconnected nature of European electricity markets and the significant influence of cross-border interactions. In addition, while the Russia–Ukraine war significantly heightened risks in European electricity markets, the panel regression does not find a significant overall effect of the COVID-19 pandemic, potentially reflecting the heterogeneous responses across countries.

Table 4
Determinants of electricity price volatility.

	Est.	Std. E.
(Intercept)	3.17***	(0.10)
Other non renewables	0.16.	(0.08)
Coal	0.01	(0.01)
Gas	−0.08*	(0.03)
Nuclear	−0.25	(0.16)
Other renewables	0.30*	(0.12)
Solar	0.04***	(0.01)
Wind	−0.01	(0.01)
EUA	0.13	(0.14)
Gas price	−0.22***	(0.06)
Oil price	0.19	(0.16)
Coal price	0.17	(0.21)
Country-specific load	0.37.	(0.19)
Total load	0.63***	(0.13)
Stoxx	−1.08***	(0.04)
COVID	0.05	(0.10)
Ukraine	1.33***	(0.06)

The table reports results from a panel regression on the electricity price volatility with heteroscedasticity and serial correlation robust standard errors by Amemiya [38]. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Regarding generation technologies, the panel regression results confirm the stabilizing effect of gas power observed in Greece, Hungary, and Italy. The risk-mitigating impact of gas power outweighs the contrary effects observed in Estonia, Finland, and Denmark, resulting in an overall reduction in volatility associated with a higher share of gas power. However, the analysis reveals a slight positive relationship between non-renewable generation and volatility, which is significant at the 10% level. This may reflect the divergent country-specific effects observed in the earlier analysis, where non-renewables were associated with reduced volatility in Denmark, Norway, Spain, and Greece, but heightened volatility in Finland and Sweden.

Consistent with the country-specific regressions, an increase in the shares of renewables and solar power are associated with higher market volatility. This finding underscores the challenges posed by the integration of variable renewable energy sources into the electricity grid.

[7] The Hausman test supports the random effects model over the fixed effects specification, and we therefore report only the results from the random effects model.

However, the panel regression results do not confirm the risk-mitigating effect of wind power identified in the country-specific regressions for Switzerland, Germany, Estonia, Italy, and Poland. This is consistent with substantial cross-country heterogeneity: Spain exhibits a volatility-increasing effect of wind power, while in the remaining markets the wind coefficient is not statistically significant. Taken together, these stabilizing, destabilizing, and insignificant effects tend to average out in the panel, suggesting that the impact of wind power on volatility is highly market-specific rather than uniform across Europe.

Overall, the results underscore the significant relationship between the composition of power generation and electricity market risk in Europe. While gas, nuclear, and partly wind power demonstrate the potential to stabilize electricity markets, an increase in the shares of renewables and solar power is associated with greater volatility, aligning with prior findings from Johnson and Oliver [1],Ballester and Furió [3],Clò et al. [13],Figueiredo and da Silva [15],Sapio [20]. However, the observed effects vary across countries, indicating that the impact of generation technologies on market volatility is shaped by country-specific market characteristics. This highlights the importance of considering local contexts when formulating policies to manage electricity market risks.

4.1. Robustness and sensitivity analyses

We conduct several additional analyses to evaluate the robustness of our results, see Appendix C for the results. Drawing from prior literature on volatility spillover effects in European electricity markets, such as Ma et al. [24] and Sikorska-Pastuszka and Papiez [26], daily electricity price volatility is quantified using the intraday price range, which reflects the difference between the maximum and minimum hourly prices observed each day. The country-specific results exhibit minor variations, but the primary conclusions, particularly the direction of the effects, remain consistent. In the panel regression model, we observe that the share of gas power does not have a significant impact on volatility, while nuclear power demonstrates a significant stabilizing effect on electricity markets, reinforcing the findings from the country-specific analyses.

Moreover, while our primary analysis focuses on the overall Stoxx Europe 600 index, we assess whether a narrower focus on the performance of the industrial sector within the broader European market influences the results by including the STOXX Europe 600 Industrial Goods & Services (SXNP) index. The results remain consistent, with the exception of gas, which remains insignificant in the panel regression model. Nevertheless, as all other findings remain unchanged, this underscores the robustness of our conclusions.

In addition, as the share of some fossil technologies is rather limited, we explore whether a more aggregated approach to generation technologies yields different results. While the main analysis distinguishes between coal, gas, and other non-renewables (such as oil and waste), we now combine them into a single category of non-renewables. Overall, the findings regarding the impact of fuel and emission prices, as well as the shares of solar, wind, and renewables, remain largely consistent with previous results. However, notable differences emerge in the effect of the share of non-renewables. In France and Greece (and Germany), a higher share of non-renewables reduces risks, reflecting the stabilizing effects previously attributed to gas (and coal) power, whereas in Denmark, Finland, and Sweden, volatility increases, consistent with the positive association between non-renewables and gas observed in the original analysis. Conversely, in countries like Spain, Estonia, Hungary, Italy, and Norway, the countervailing effects of gas and coal power offset each other, resulting in a non-significant relationship between the aggregated share of non-renewables and electricity price volatility.

In conclusion, our robustness analyses affirm the reliability of the main findings. Through testing alternative model specifications, including a more focused analysis of the industrial sector and aggregated generation technologies, the results remain broadly consistent. These robustness checks underscore the stability of our results and reinforce the validity of our conclusions.

5. Conclusion

To mitigate the escalating threats of anthropogenic climate change, shift from a fossil fuel-dependent global energy system to one centered on renewable, carbon-free resources is indispensable. However, the intermittent nature of renewable energy generation introduces significant challenges to electricity markets. Johnson and Oliver [1] state two countervailing effects of renewable energy sources on price variability. First, the stochastic merit-order effect, which reduces price volatility by shifting the supply curve outward. Second, the intermittency effect, which amplifies volatility due to the unpredictable nature of renewable generation.

This study provides a comprehensive analysis of the determinants of electricity price volatility in European wholesale electricity markets, with a particular focus on the role of renewable energy sources. Using country-specific and panel regression models, we identify total electricity demand and the Russia–Ukraine war as significant drivers of market risk, whereas macroeconomic factors, such as fuel prices and broader economic activity, play a comparatively minor role. Regarding electricity generation, conventional power sources, such as nuclear and coal, exhibit a stabilizing effect on electricity prices. In contrast, solar power is associated with increased price volatility, reflecting the dominance of the intermittency effect, consistent with previous findings in the literature. Wind power, however, demonstrates a stabilizing effect in most of the studied markets, although heightened volatility is observed in Spain.

The analysis also highlights substantial heterogeneity in effects across countries, emphasizing the importance of local market characteristics and the interaction between generation technologies and electricity demand. These findings underscore the need for further research to investigate the specific dynamics of individual European electricity markets and their evolving generation portfolios. A deeper understanding of these characteristics is crucial for designing tailored policies that enhance market stability while accommodating the increasing penetration of renewable energy sources.

At the same time, several limitations of this study should be acknowledged. First, our baseline empirical strategy relies on linear regression specifications. While this approach is well suited to estimating average marginal effects and yields transparent interpretation, it may not fully capture nonlinearities, asymmetric responses, or threshold effects in the volatility response, for instance if the effect of renewables or load changes once certain system conditions are reached. Second, although our focus on intraday volatility and the largely predetermined nature of short-run demand and non-dispatchable renewable generation mitigates standard simultaneity concerns, residual endogeneity cannot be fully ruled out. Load, the contemporaneous generation mix, and volatility may still be jointly affected by unobserved system conditions, which could bias estimates. Third, our analysis is confined to day-ahead wholesale prices and therefore does not speak directly to intraday or balancing markets, where price formation and the transmission of renewable shocks and demand fluctuations may differ due to forecasting updates, liquidity, and balancing requirements. Finally, while the multi-country design enhances external validity, institutional and market-design differences across countries, such as capacity mechanisms, renewable support schemes, bidding rules, and congestion management, are only indirectly captured in our baseline framework. A more explicit modeling of these features and of how they mediate volatility responses is left for future research.

Overall, our findings underline the critical need for tailored energy policies that account for the dual objectives of integrating renewable energy sources and maintaining electricity market stability. By advancing the understanding of electricity price volatility and its drivers, this research provides a basis for policymakers to design targeted energy policies and market regulations that enhance system resilience, promote the efficient integration of renewable and conventional energy sources, and support the transition to a sustainable, low-carbon future.

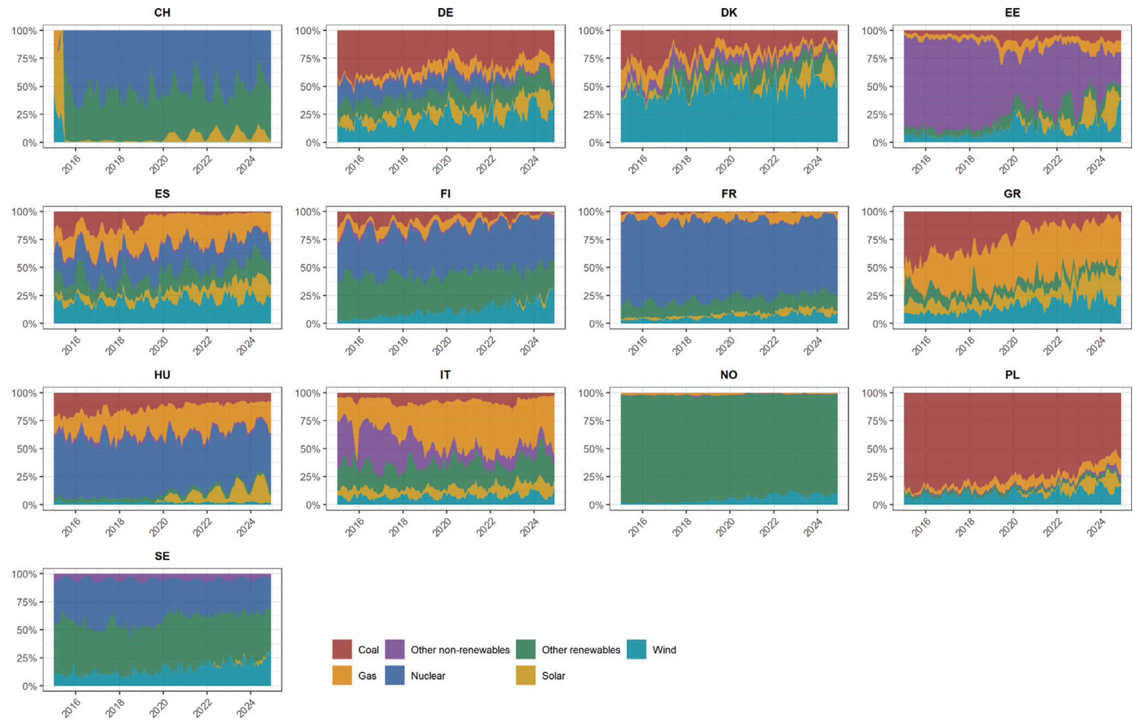

Fig. 1. Overview of technology mix in European electricity markets.
These plots display the average monthly technology share in Switzerland (CH), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Greece (GR), Hungary (HU), Italy (IT), Norway (NO), Poland (PL) and Sweden (SE).

CRediT authorship contribution statement

Amelie Schischke: Conceptualization, Methodology, Software, Data curation, Validation, Writing – original draft. **Andreas W. Rathgeber:** Supervision, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

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Appendix A. Data

A.1. Data preprocessing

The construction of the variables proceeds in several steps.

- Hourly data on day-ahead electricity prices, generation by technology, and load are collected from ENTSO-E Transparency Platform [39], while daily data on fuel prices, EUA prices, and the Stoxx Europe 600 index are obtained from Datastream [42].
- All hourly series are first aligned to a common UTC time standard and then aggregated to daily frequency: realized volatility is computed from hourly prices for each country according to Eq. (3), and hourly generation and load are summed to daily values. Technology shares are calculated as the ratio of daily generation from each technology to total daily generation.
- The resulting time series are inspected for obvious recording errors. When isolated outliers are identified, the affected observation is replaced by the preceding day's value to avoid undue influence on the regression estimates.
- To address non-stationarity, the volatility measure is transformed using the natural logarithm, and daily logarithmic returns are computed for all exogenous variables (technology shares, domestic and aggregate European load, fuel and emission prices, and the Stoxx Europe 600 index). This yields stationary regressors and helps to avoid spurious regression results.

A.2. Data description

See Figs. 1, 2 and Table 5.

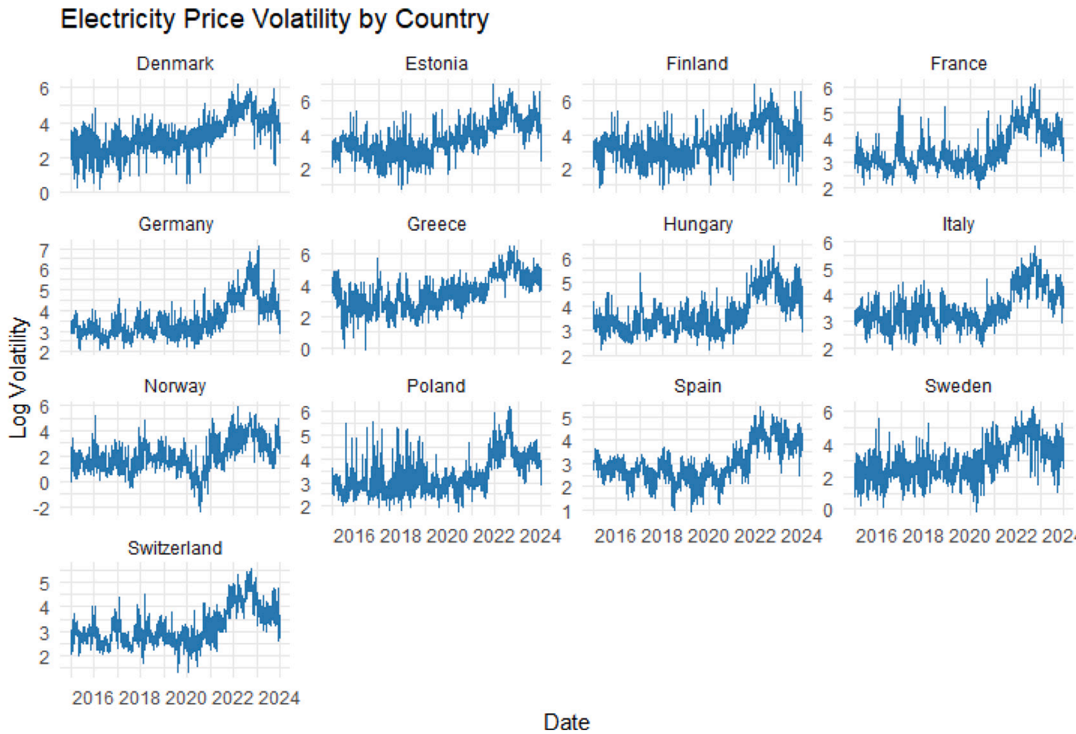

Fig. 2. Time series of electricity price volatility in 13 European markets.
The figure displays the daily logarithmized volatility of wholesale electricity prices for each of the 13 analyzed European markets: Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Norway, Poland, Spain, Sweden, and Switzerland.

Table 5
Descriptive statistics for the explanatory variables.

	Minimum	Median	Mean	Maximum	St.Dev.	Skewness	Kurtosis	ADF
EUA	−0.19	0.00	0.00	0.17	0.03	−0.42	7.31	−49.54**
Gas price	−0.35	−0.00	0.00	0.38	0.04	0.28	17.71	−44.86**
Oil price	−0.26	0.00	0.00	0.13	0.02	−0.90	14.56	−50.59**
Coal price	−0.24	0.00	0.00	0.40	0.03	1.01	28.95	−41.90**
STOXX	−0.13	0.00	0.00	0.08	0.01	−0.96	14.94	−46.91**
STOXX Industrials	−0.14	0.00	0.00	0.10	0.01	−0.63	11.92	−46.41**
Country-specific load CH	−0.23	−0.00	−0.00	0.25	0.04	0.27	9.22	−59.49**
Country-specific load DE	−0.28	0.00	−0.00	0.29	0.05	−0.10	15.69	−61.31**
Country-specific load DK	−0.23	0.00	0.00	0.21	0.04	0.26	7.24	−57.61**
Country-specific load EE	−0.37	0.00	−0.00	0.37	0.04	0.01	14.30	−58.61**
Country-specific load ES	−0.25	−0.00	−0.00	0.25	0.04	0.07	11.50	−56.32**
Country-specific load FI	−0.25	0.00	−0.00	0.27	0.03	−0.10	9.84	−50.43**
Country-specific load FR	−0.32	0.00	−0.00	0.35	0.05	0.05	9.11	−52.50**
Country-specific load GR	−0.35	0.00	−0.00	0.29	0.05	−0.21	8.11	−50.72**
Country-specific load HU	−0.30	0.00	−0.00	0.29	0.05	−0.12	14.24	−61.01**
Country-specific load IT	−0.49	−0.00	−0.00	0.43	0.07	−0.12	17.42	−61.06**
Country-specific load NO	−0.15	0.00	0.00	0.21	0.03	0.22	6.73	−48.16**
Country-specific load PL	−0.41	0.00	−0.00	0.34	0.06	−0.76	19.19	−64.91**
Country-specific load SE	−0.21	−0.00	−0.00	0.24	0.04	0.39	6.73	−54.84**
Country-specific load	−0.24	0.00	0.00	0.28	0.04	0.29	17.07	−57.03**
CH wind	−5.66	−0.00	−0.00	4.68	0.97	−0.16	5.30	−65.40**
CH solar	−5.61	0.00	0.01	5.53	0.85	−0.05	9.32	−73.15**
CH nuclear	−1.13	0.00	0.00	1.30	0.14	0.00	15.96	−53.31**
CH gas	−3.00	0.00	−0.00	2.14	0.09	−13.85	698.19	−59.50**
CH other renewables	−1.19	0.00	−0.00	1.28	0.17	0.02	8.86	−60.61**
DE coal	−1.19	0.00	−0.00	1.04	0.24	−0.42	6.01	−55.47**
DE wind	−2.65	−0.02	0.00	2.65	0.65	0.02	3.54	−56.23**
DE nuclear	−0.62	0.00	−0.00	0.56	0.09	−0.13	7.89	−57.40**
DE other renewables	−0.37	−0.00	0.00	0.39	0.08	0.01	4.14	−65.34**
DE gas	−1.40	0.00	0.00	1.18	0.29	−0.12	4.67	−58.95**
DE other fossil fuels	−0.48	0.00	0.00	0.47	0.11	−0.12	4.36	−61.11**
DE solar	−2.14	0.01	0.00	1.63	0.42	−0.19	4.50	−65.72**
DK wind	−2.49	−0.00	0.00	2.47	0.61	0.10	4.58	−61.86**
DK coal	−2.53	−0.00	−0.00	2.79	0.52	−0.09	4.41	−61.02**

(continued on next page)

Table 5 (*continued*).

	Minimum	Median	Mean	Maximum	St.Dev.	Skewness	Kurtosis	ADF
DK gas	−1.83	−0.02	−0.00	1.98	0.50	−0.01	3.64	−64.50**
DK other fossil fuels	−1.24	0.01	−0.00	1.65	0.34	−0.04	3.72	−63.22**
DK other renewables	−3.87	0.01	0.00	4.10	0.58	−0.09	10.80	−57.96**
DK solar	−2.87	0.03	0.00	2.90	0.75	−0.09	3.81	−68.81**
EE other fossil fuels	−2.25	0.00	−0.00	2.21	0.22	0.02	36.75	−53.02**
EE wind	−2.69	−0.01	0.00	3.88	0.81	0.17	3.77	−61.87**
EE other renewables	−0.84	0.00	0.00	0.85	0.16	0.16	6.26	−54.90**
EE gas	−1.22	0.00	0.00	1.17	0.23	−0.08	6.15	−55.55**
EE coal	−1.58	0.00	0.00	1.52	0.26	−0.14	7.91	−54.98**
EE solar	−3.52	0.00	0.00	3.74	0.52	−0.04	11.08	−69.29**
ES nuclear	−0.39	0.00	0.00	0.36	0.07	−0.27	6.51	−51.97**
ES other renewables	−0.49	−0.00	0.00	0.52	0.14	0.03	3.68	−63.04**
ES coal	−4.02	0.00	−0.00	4.64	0.29	0.35	52.11	−55.71**
ES gas	−1.00	0.01	0.00	1.29	0.24	0.01	5.16	−55.21**
ES wind	−2.07	−0.00	0.00	2.08	0.50	−0.03	3.96	−56.57**
ES solar	−1.94	0.00	0.00	1.89	0.38	−0.10	5.98	−59.04**
ES other fossil fuels	−0.46	0.00	−0.00	0.41	0.08	−0.21	5.48	−56.40**
FI nuclear	−0.37	0.00	0.00	0.40	0.08	−0.04	6.42	−55.35**
FI other renewables	−0.60	−0.00	−0.00	0.62	0.11	0.04	6.72	−59.47**
FI gas	−1.53	−0.00	−0.00	1.08	0.20	−0.45	11.67	−54.90**
FI coal	−5.94	0.00	−0.00	6.08	0.38	−0.00	68.96	−53.75**
FI other fossil fuels	−1.77	0.00	−0.00	1.71	0.22	−0.37	16.65	−57.06**
FI wind	−2.64	−0.00	0.00	3.32	0.71	0.14	3.80	−60.02**
FI solar	−1.15	0.00	−0.00	1.10	0.12	−0.95	32.95	−67.98**
FR nuclear	−0.18	−0.00	−0.00	0.19	0.03	0.03	6.40	−58.69**
FR other renewables	−0.43	−0.00	0.00	0.52	0.09	0.19	5.21	−56.99**
FR gas	−2.18	0.01	−0.00	1.53	0.30	−0.32	9.25	−58.05**
FR wind	−1.87	−0.01	0.00	2.03	0.56	0.15	3.25	−58.49**
FR coal	−6.99	0.01	−0.00	5.26	1.11	−0.25	10.23	−55.24**
FR other fossil fuels	−1.53	0.00	−0.00	1.22	0.21	−0.26	11.19	−62.40**
FR solar	−1.09	0.00	0.00	1.12	0.28	−0.20	3.92	−68.31**
GR coal	−2.54	0.00	0.00	9.18	0.31	11.46	360.73	−50.02**
GR other renewables	−1.08	−0.00	0.00	1.45	0.26	0.18	5.05	−64.66**
GR wind	−2.52	−0.01	−0.00	3.15	0.74	0.11	3.65	−57.47**
GR gas	−1.29	0.01	0.00	1.10	0.22	−0.17	5.64	−59.30**
GR solar	−1.84	−0.00	0.00	2.26	0.41	−0.05	6.79	−66.27**
GR other fossil fuels	−1.36	0.00	0.00	1.83	0.08	7.53	343.29	−78.88**
HU nuclear	−0.35	−0.00	0.00	0.34	0.06	0.27	7.45	−53.27**
HU coal	−4.62	0.00	−0.00	6.47	0.25	4.55	266.48	−54.46**
HU gas	−0.90	0.00	0.00	0.99	0.15	−0.29	8.66	−57.39**
HU other renewables	−0.71	−0.00	0.00	0.71	0.11	0.16	7.98	−52.22**
HU other fossil fuels	−0.50	−0.00	−0.00	0.66	0.12	0.17	6.51	−61.64**
HU wind	−5.21	−0.01	−0.00	5.81	1.21	0.11	4.24	−64.44**
HU solar	−2.50	0.00	0.00	2.39	0.42	−0.01	10.59	−72.69**
IT other fossil fuels	−2.36	0.00	−0.00	2.00	0.12	−3.23	166.22	−52.34**
IT other renewables	−0.52	−0.00	−0.00	0.54	0.08	0.20	6.98	−60.16**
IT gas	−3.32	0.00	0.00	3.44	0.18	−0.02	197.29	−59.85**
IT wind	−2.43	−0.01	−0.00	2.87	0.71	0.11	3.42	−57.18**
IT solar	−1.96	−0.00	−0.00	1.53	0.32	−0.18	6.25	−65.29**
IT coal	−2.82	0.00	0.00	4.16	0.20	1.86	114.17	−53.06**
NO other renewables	−0.18	0.00	−0.00	0.26	0.03	0.18	10.15	−57.37**
NO wind	−2.51	−0.00	0.00	2.14	0.56	−0.05	3.98	−58.89**
NO gas	−2.53	0.00	0.00	3.11	0.18	0.10	75.91	−51.82**
NO other fossil fuels	−3.20	0.00	0.00	2.28	0.40	−0.42	14.02	−54.49**
PL wind	−2.66	−0.02	0.00	2.94	0.74	0.13	3.54	−59.95**
PL other fossil fuels	−0.47	0.00	0.00	0.47	0.06	0.42	9.90	−58.61**
PL gas	−0.94	0.00	0.00	0.71	0.12	−0.33	8.75	−52.31**
PL coal	−0.40	0.00	−0.00	0.41	0.08	−0.28	5.66	−58.61**
PL other renewables	−0.65	0.00	0.00	0.91	0.15	0.04	5.11	−66.57**
PL solar	−1.68	0.00	0.00	1.60	0.26	−0.13	10.87	−69.34**
SE other renewables	−0.80	0.00	−0.00	1.03	0.15	0.03	6.91	−58.41**
SE nuclear	−0.37	0.00	0.00	0.28	0.06	−0.45	6.50	−51.90**
SE other fossil fuels	−0.55	0.00	−0.00	0.69	0.11	0.15	6.18	−52.01**
SE wind	−2.50	−0.00	0.00	1.92	0.52	−0.00	3.99	−56.67**
SE gas	−1.26	0.00	0.00	2.21	0.08	10.32	379.03	−49.48**
SE solar	−2.33	0.00	0.00	1.83	0.27	0.07	19.86	−73.28**

This table displays the minimum, median, mean, maximum, standard deviation (St.Dev.), skewness and kurtosis of the logarithmic returns for the explanatory variables. Moreover, the test statistics of the Augmented Dickey Fuller (ADF) test are reported, whereby ** indicate significance at the 1% level. The explanatory variables are the shares of coal, gas, other fossil fuels (oil, waste and other), nuclear, solar, wind, and other renewables (biomass, geothermal, hydro, and other) as well as the country-specific load of the analyzed countries Switzerland (CH), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Greece (GR), Hungary (HU), Italy (IT), Norway (NO), Poland (PL), and Sweden (SE). In addition, the prices of Brent oil futures (Oil price), TTF Natural Gas futures (Gas price), and API2 Rotterdam Coal futures (Coal price), the EU Allowance (EUA) price, and the Stoxx Europe 600 index (STOXX) and STOXX Europe 600 Industrial Goods & Services (SXNP) index (STOXX Industrials) are also reported.

Table 6
Country-specific determinants of electricity price volatility.

	Denmark		Estonia		Finland		France		Germany		Greece		Hungary		Italy		Norway		Poland		Spain		Sweden		Switzerland	
	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.
(Intercept)	2.94***	(0.07)	3.30***	(0.08)	3.22***	(0.07)	3.26***	(0.07)	3.21***	(0.05)	3.04***	(0.05)	3.44***	(0.06)	3.25***	(0.04)	1.69***	(0.07)	3.08***	(0.05)	2.73***	(0.06)	2.56***	(0.07)	2.91***	(0.05)
Other non-renewables	−0.19*	(0.08)	0.05	(0.04)	0.20**	(0.07)	0.04	(0.04)	−0.15	(0.10)	−0.27*	(0.13)	0.01	(0.06)	−0.03	(0.07)	−0.06*	(0.03)	0.33.	(0.19)	−0.33*	(0.14)	0.74***	(0.17)		
Coal	0.07	(0.05)	−0.24*	(0.12)	0.17.	(0.09)	0.00	(0.01)	−0.12	(0.07)	−0.01	(0.04)	−0.04	(0.03)	−0.01	(0.04)			−0.15	(0.18)	−0.08*	(0.04)				
Gas	0.23***	(0.05)	0.23	(0.14)	0.16*	(0.07)	−0.14***	(0.03)	0.01	(0.05)	−0.27**	(0.08)	−0.12.	(0.06)	−0.08*	(0.04)	−0.02	(0.09)	−0.11	(0.10)	0.13.	(0.07)	−0.19	(0.39)	−0.04	(0.07)
Nuclear					0.26	(0.26)	−0.58.	(0.31)	−0.82***	(0.20)			−0.24	(0.23)							0.17	(0.21)	−0.13	(0.36)	−0.20.	(0.11)
Other renewables	0.03	(0.03)	−0.15.	(0.08)	0.33.	(0.18)	0.23*	(0.11)	0.60***	(0.17)	0.19***	(0.05)	0.04	(0.08)	0.04	(0.15)	0.22	(0.63)	−0.02	(0.06)	0.37***	(0.07)	0.04	(0.19)	−0.13	(0.09)
Solar	0.02	(0.02)	0.01	(0.02)	0.10	(0.14)	−0.01	(0.03)	0.05*	(0.02)	0.03	(0.04)	0.02	(0.02)	0.00	(0.03)			0.01	(0.03)	0.08***	(0.02)	0.04	(0.04)	0.01	(0.01)
Wind	0.00	(0.03)	−0.07***	(0.01)	−0.02	(0.03)	−0.04.	(0.02)	−0.09***	(0.02)	−0.02	(0.03)	0.00	(0.01)	−0.04*	(0.02)	0.01	(0.03)	−0.13***	(0.02)	0.22***	(0.03)	−0.11*	(0.05)	−0.02**	(0.01)
EUA	−0.36	(0.59)	0.59	(0.54)	−0.07	(0.60)	−0.15	(0.44)	0.35	(0.45)	0.20	(0.59)	0.63	(0.39)	0.22	(0.37)	0.42	(0.80)	0.39	(0.54)	−0.05	(0.43)	−0.43	(0.70)	−0.12	(0.43)
Gas price	0.04	(0.64)	0.11	(0.53)	−0.11	(0.61)	−0.23	(0.49)	−0.40	(0.56)	−0.10	(0.85)	−0.37	(0.47)	−0.30	(0.62)	−0.28	(0.73)	0.49	(0.54)	−0.19	(0.52)	−0.71	(0.78)	0.13	(0.65)
Oil price	0.75	(0.63)	0.77	(0.54)	−0.40	(0.64)	0.19	(0.49)	0.01	(0.46)	0.22	(0.63)	0.30	(0.42)	0.39	(0.43)	0.33	(0.78)	0.36	(0.51)	0.91*	(0.45)	−0.02	(0.88)	0.03	(0.50)
Coal price	0.23	(0.70)	0.17	(0.68)	0.77	(0.75)	0.16	(0.65)	0.19	(0.72)	−0.44	(0.96)	0.29	(0.65)	0.46	(0.73)	0.03	(0.95)	−0.21	(0.58)	−0.59	(0.71)	1.09	(0.94)	0.33	(0.75)
Country-specific load	1.31***	(0.37)	0.38	(0.30)	1.83***	(0.49)	0.57*	(0.25)	0.36	(0.35)	−0.39	(0.32)	0.15	(0.17)	0.44*	(0.19)	1.96**	(0.60)	0.64**	(0.24)	−0.07	(0.25)	1.15**	(0.36)	0.69**	(0.26)
Total load	0.02	(0.42)	0.90**	(0.33)	1.21**	(0.39)	0.50	(0.33)	0.23	(0.56)	0.34	(0.42)	0.44	(0.29)	−0.26	(0.37)	1.25**	(0.40)	0.13	(0.38)	0.43	(0.26)	1.61***	(0.44)	0.43	(0.30)
Stoxx	−1.78	(1.30)	−2.72*	(1.20)	−1.11	(1.45)	−1.07	(0.88)	−1.01	(1.08)	−0.04	(1.42)	−0.91	(0.93)	−0.59	(1.01)	−1.45	(1.50)	−2.63*	(1.15)	−1.39	(0.89)	−0.46	(2.16)	−0.86	(1.13)
COVID	0.44***	(0.09)	0.56***	(0.10)	0.49***	(0.10)	−0.11	(0.12)	0.06	(0.07)	0.46***	(0.06)	−0.18*	(0.08)	−0.11.	(0.06)	−0.55.	(0.32)	−0.05	(0.07)	−0.02	(0.11)	0.58***	(0.11)	−0.02	(0.07)
Ukraine	1.57***	(0.12)	1.75***	(0.14)	1.18***	(0.18)	1.24***	(0.13)	1.55***	(0.11)	1.81***	(0.08)	1.28***	(0.10)	1.22***	(0.09)	1.65***	(0.16)	1.27***	(0.11)	1.38***	(0.08)	1.64***	(0.14)	1.22***	(0.09)

The table reports results from the OLS regressions on the country-specific electricity price volatility with Newey–West standard errors to correct for heteroscedasticity and autocorrelation for Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Norway, Poland, Spain, Sweden and Switzerland. The standard errors are reported in brackets. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Table 7
Country-specific determinants of electricity price volatility, using the intraday range.

	Denmark		Estonia		Finland		France		Germany		Greece		Hungary		Italy		Norway		Poland		Spain		Sweden		Switzerland	
	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.
(Intercept)	3.20***	(0.07)	3.47***	(0.08)	3.41***	(0.07)	3.50***	(0.06)	3.46***	(0.04)	3.02***	(0.07)	3.74***	(0.05)	3.50***	(0.03)	2.04***	(0.08)	3.34***	(0.05)	2.99***	(0.06)	2.87***	(0.06)	3.21***	(0.04)
Other non renewables	−0.29***	(0.08)	0.07*	(0.03)	0.17**	(0.06)	0.05	(0.04)	−0.17	(0.11)	−0.26	(0.18)	−0.01	(0.06)	−0.04	(0.07)	−0.05.	(0.03)	0.09	(0.18)	−0.78***	(0.15)	0.68***	(0.16)		
Coal	0.10*	(0.05)	−0.15	(0.10)	0.15.	(0.09)	0.01	(0.01)	−0.10	(0.08)	0.00	(0.05)	−0.02	(0.03)	−0.04	(0.04)			0.11	(0.19)	−0.06.	(0.04)				
Gas	0.27***	(0.05)	0.11	(0.11)	0.23***	(0.07)	−0.11**	(0.03)	0.05	(0.05)	−0.18*	(0.08)	−0.09	(0.06)	−0.08*	(0.04)	−0.04	(0.09)	−0.14	(0.10)	0.39***	(0.08)	−0.27	(0.34)	−0.02	(0.05)
Nuclear					0.15	(0.23)	−0.49	(0.35)	−0.85***	(0.19)			−0.12	(0.23)							0.15	(0.22)	0.08	(0.35)	−0.29*	(0.12)
Other renewables	0.04	(0.03)	−0.15*	(0.07)	0.41*	(0.17)	0.52***	(0.12)	0.83***	(0.18)	0.26***	(0.05)	0.00	(0.08)	0.19	(0.14)	0.62	(0.56)	−0.10.	(0.06)	0.74***	(0.08)	0.26	(0.17)	−0.07	(0.10)
Solar	0.04**	(0.01)	0.00	(0.02)	0.17	(0.15)	−0.03	(0.03)	0.01	(0.02)	0.06	(0.04)	0.02	(0.02)	0.02	(0.02)			0.03	(0.03)	0.11***	(0.02)	0.04	(0.05)	0.00	(0.01)
Wind	0.02	(0.03)	−0.06***	(0.01)	−0.02	(0.02)	−0.05*	(0.02)	−0.07**	(0.02)	−0.01	(0.03)	0.00	(0.01)	−0.03**	(0.01)	0.01	(0.03)	−0.12***	(0.02)	0.29***	(0.04)	−0.06	(0.05)	−0.03***	(0.01)
EUA	−0.28	(0.58)	0.28	(0.48)	−0.21	(0.55)	−0.25	(0.46)	0.19	(0.47)	0.23	(0.62)	0.39	(0.41)	0.12	(0.39)	0.31	(0.74)	0.46	(0.50)	0.20	(0.46)	−0.41	(0.68)	−0.21	(0.45)
Gas price	0.25	(0.65)	0.19	(0.53)	0.16	(0.61)	−0.26	(0.51)	−0.23	(0.59)	−0.07	(0.92)	−0.07	(0.48)	−0.12	(0.54)	−0.46	(0.73)	0.30	(0.52)	−0.33	(0.52)	−0.56	(0.84)	0.21	(0.70)
Oil price	0.84	(0.65)	0.50	(0.51)	−0.27	(0.63)	0.01	(0.50)	0.03	(0.49)	0.01	(0.66)	0.42	(0.43)	0.05	(0.44)	0.52	(0.74)	0.27	(0.51)	0.69	(0.51)	0.31	(0.88)	−0.30	(0.52)
Coal price	0.01	(0.73)	−0.09	(0.63)	0.59	(0.70)	0.24	(0.67)	−0.08	(0.76)	−0.33	(1.06)	−0.09	(0.65)	0.35	(0.64)	−0.06	(0.92)	−0.14	(0.55)	−0.52	(0.66)	0.84	(0.99)	0.21	(0.82)
Country-specific load	1.42***	(0.38)	0.63*	(0.26)	1.70***	(0.47)	0.70**	(0.25)	0.17	(0.39)	−0.40	(0.35)	0.00	(0.18)	0.04	(0.20)	2.14***	(0.57)	0.60*	(0.26)	−0.44	(0.28)	1.43***	(0.39)	0.88**	(0.30)
Total load	0.00	(0.46)	1.29***	(0.29)	1.51***	(0.36)	0.50	(0.36)	0.41	(0.62)	0.58	(0.44)	0.96**	(0.32)	0.37	(0.40)	1.27***	(0.38)	0.18	(0.37)	0.43	(0.33)	1.70***	(0.42)	0.37	(0.36)
Stoxx	−1.09	(1.26)	−2.03*	(1.01)	−0.67	(1.41)	−1.09	(0.92)	−1.10	(1.09)	0.30	(1.52)	−0.89	(0.96)	−0.47	(1.00)	−1.19	(1.46)	−2.50*	(1.12)	−1.23	(1.17)	−0.46	(2.15)	−0.74	(1.17)
COVID	0.38***	(0.09)	0.48***	(0.10)	0.44***	(0.09)	−0.14	(0.11)	0.05	(0.06)	0.53***	(0.08)	−0.18*	(0.08)	−0.09.	(0.05)	−0.59	(0.36)	−0.22**	(0.08)	−0.06	(0.13)	0.50***	(0.10)	−0.05	(0.07)
Ukraine	1.56***	(0.11)	1.64***	(0.14)	1.22***	(0.17)	1.18***	(0.12)	1.46***	(0.09)	1.96***	(0.10)	1.20***	(0.09)	1.16***	(0.07)	1.57***	(0.18)	1.16***	(0.10)	1.27***	(0.08)	1.56***	(0.12)	1.13***	(0.08)

The table reports results from the OLS regressions on the country-specific electricity price volatility with Newey–West standard errors to correct for heteroscedasticity and autocorrelation for Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Norway, Poland, Spain, Sweden and Switzerland. Hereby, the volatility is calculated based on the intraday range, instead of the realized volatility. The standard errors are reported in brackets. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Table 8
Country-specific determinants of electricity price volatility, using the intraday range.

	Est.	Std. E.
(Intercept)	3.42***	(0.11)
Other non renewables	0.14.	(0.07)
Coal	0.01	(0.01)
Gas	−0.02	(0.03)
Nuclear	−0.31.	(0.17)
Other renewables	0.47***	(0.13)
Solar	0.03***	(0.01)
Wind	−0.01	(0.01)
EUA	0.04	(0.11)
Gas price	−0.10	(0.08)
Oil price	0.15	(0.11)
Coal price	0.04	(0.18)
Country-specific load	0.28	(0.20)
Total load	0.79***	(0.20)
Stoxx	−1.01***	(0.08)
COVID	0.02	(0.10)
Ukraine	1.26***	(0.04)

The table reports results from a panel regression on electricity price volatility with heteroscedasticity and serial correlation robust standard errors by Amemiya [38]. Hereby, the volatility is calculated based on the intraday range, instead of the realized volatility.x Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Appendix B. Empirical results

See Table 6.

Appendix C. Robustness and sensitivity analyses

C.1. Different volatility measure: intraday range

See Tables 7 and 8.

C.2. Different proxy for economic activity

See Tables 9 and 10.

C.3. Aggregation of fossil fuels

See Tables 11 and 12.

Table 9
Country-specific determinants of electricity price volatility, using the STOXX Europe 600 Industrial Goods & Services (SXNP) index.

	Denmark		Estonia		Finland		France		Germany		Greece		Hungary		Italy		Norway		Poland		Spain		Sweden		Switzerland	
	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.
(Intercept)	2.94***	(0.07)	3.30***	(0.08)	3.22***	(0.07)	3.26***	(0.07)	3.21***	(0.05)	3.04***	(0.05)	3.44***	(0.06)	3.25***	(0.04)	1.69***	(0.07)	3.08***	(0.05)	2.73***	(0.06)	2.56***	(0.07)	2.91***	(0.05)
Other non renewables	−0.19*	(0.08)	0.05	(0.04)	0.20**	(0.07)	0.04	(0.04)	−0.15	(0.10)	−0.27*	(0.13)	0.01	(0.06)	−0.03	(0.07)	−0.06*	(0.03)	0.33.	(0.19)	−0.33*	(0.14)	0.74***	(0.17)		
Coal	0.07	(0.05)	−0.24.	(0.12)	0.17.	(0.09)	0.00	(0.01)	−0.12	(0.07)	−0.01	(0.04)	−0.04	(0.03)	−0.01	(0.04)			−0.15	(0.18)	−0.08*	(0.04)				
Gas	0.23***	(0.05)	0.23	(0.14)	0.16*	(0.08)	−0.14***	(0.03)	0.01	(0.05)	−0.27**	(0.08)	−0.12*	(0.06)	−0.08*	(0.04)	−0.02	(0.09)	−0.11	(0.10)	0.13.	(0.08)	−0.19	(0.39)	−0.05	(0.07)
Nuclear					0.26	(0.26)	−0.57.	(0.31)	−0.82***	(0.20)			−0.24	(0.23)							0.17	(0.21)	−0.13	(0.36)	−0.20.	(0.11)
Other renewables	0.03	(0.03)	−0.15.	(0.08)	0.33.	(0.18)	0.23*	(0.11)	0.60***	(0.17)	0.19***	(0.05)	0.04	(0.08)	0.04	(0.14)	0.21	(0.63)	−0.02	(0.06)	0.37***	(0.06)	0.04	(0.18)	−0.14	(0.09)
Solar	0.02	(0.02)	0.01	(0.02)	0.10	(0.14)	−0.01	(0.03)	0.05*	(0.02)	0.03	(0.04)	0.02	(0.02)	0.00	(0.02)			0.01	(0.03)	0.09***	(0.02)	0.04	(0.04)	0.01	(0.01)
Wind	0.00	(0.03)	−0.07***	(0.01)	−0.02	(0.03)	−0.04.	(0.02)	−0.09***	(0.02)	−0.02	(0.03)	0.00	(0.01)	−0.04**	(0.01)	0.01	(0.03)	−0.13***	(0.02)	0.22***	(0.03)	−0.11*	(0.05)	−0.02**	(0.01)
EUA	−0.32	(0.58)	0.60	(0.54)	−0.06	(0.61)	−0.09	(0.44)	0.41	(0.45)	0.23	(0.59)	0.70.	(0.40)	0.29	(0.37)	0.44	(0.81)	0.43	(0.53)	0.01	(0.42)	−0.35	(0.70)	−0.05	(0.44)
Gas price	0.04	(0.64)	0.11	(0.53)	−0.11	(0.60)	−0.23	(0.49)	−0.40	(0.56)	−0.11	(0.85)	−0.37	(0.47)	−0.31	(0.60)	−0.28	(0.73)	0.50	(0.54)	−0.19	(0.52)	−0.72	(0.78)	0.13	(0.65)
Oil price	0.75	(0.63)	0.72	(0.55)	−0.41	(0.64)	0.21	(0.49)	0.04	(0.46)	0.25	(0.63)	0.33	(0.42)	0.43	(0.43)	0.32	(0.78)	0.35	(0.51)	0.94*	(0.46)	0.04	(0.88)	0.07	(0.50)
Coal price	0.22	(0.70)	0.17	(0.67)	0.77	(0.75)	0.14	(0.65)	0.17	(0.72)	−0.45	(0.96)	0.28	(0.65)	0.44	(0.71)	0.02	(0.95)	−0.22	(0.58)	−0.61	(0.71)	1.06	(0.94)	0.31	(0.75)
Country-specific load	1.31***	(0.37)	0.38	(0.30)	1.83***	(0.49)	0.57*	(0.24)	0.36	(0.35)	−0.39	(0.32)	0.15	(0.17)	0.44*	(0.19)	1.96**	(0.60)	0.64**	(0.24)	−0.07	(0.25)	1.15**	(0.36)	0.68**	(0.26)
Total load	0.03	(0.42)	0.91**	(0.33)	1.21**	(0.39)	0.50	(0.33)	0.22	(0.56)	0.34	(0.42)	0.44	(0.29)	−0.25	(0.36)	1.26**	(0.40)	0.13	(0.38)	0.43	(0.27)	1.62***	(0.44)	0.44	(0.30)
STOXX Industrials	−1.81.	(1.08)	−2.34*	(1.05)	−0.97	(1.31)	−1.34	(0.84)	−1.27	(0.97)	−0.33	(1.21)	−1.21	(0.83)	−1.04	(0.88)	−1.33	(1.38)	−2.51*	(1.03)	−1.65*	(0.82)	−1.01	(1.79)	−1.28	(1.01)
COVID	0.44***	(0.09)	0.56***	(0.10)	0.49***	(0.10)	−0.11	(0.11)	0.06	(0.07)	0.46***	(0.06)	−0.18*	(0.08)	−0.11*	(0.06)	−0.55.	(0.32)	−0.05	(0.07)	−0.02	(0.11)	0.58***	(0.11)	−0.02	(0.07)
Ukraine	1.57***	(0.12)	1.75***	(0.14)	1.18***	(0.18)	1.24***	(0.13)	1.55***	(0.11)	1.81***	(0.08)	1.29***	(0.10)	1.22***	(0.08)	1.65***	(0.16)	1.27***	(0.11)	1.38***	(0.08)	1.64***	(0.14)	1.22***	(0.09)

The table reports results from the OLS regressions on the country-specific electricity price volatility with Newey–West standard errors to correct for heteroscedasticity and autocorrelation for Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Norway, Poland, Spain, Sweden and Switzerland. Hereby, we include the STOXX Europe 600 Industrial Goods & Services (SXNP) index focusing on the economic activity instead of the broader STOXX Europe 600 index. The standard errors are reported in brackets. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Table 10
Country-specific determinants of electricity price volatility using the STOXX Europe 600 Industrial Goods & Services (SXNP) index.

	Est.	Std. E.
(Intercept)	3.17***	(0.10)
Other non renewables	0.16.	(0.08)
Coal	0.01	(0.01)
Gas	−0.08*	(0.03)
Nuclear	−0.25	(0.16)
Other renewables	0.30*	(0.12)
Solar	0.04***	(0.01)
Wind	−0.01	(0.01)
EUA	0.18	(0.15)
Gas price	−0.23***	(0.06)
Oil price	0.21	(0.17)
Coal price	0.16	(0.21)
Country-specific load	0.37.	(0.19)
Total load	0.63***	(0.13)
STOXX Industrials	−1.27***	(0.06)
COVID	0.05	(0.10)
Ukraine	1.33***	(0.06)

The table reports results from a panel regression on electricity price volatility with heteroscedasticity and serial correlation robust standard errors by Amemiya [38]. The STOXX Europe 600 Industrial Goods & Services (SXNP) index is used to focus on economic activity instead of the broader STOXX Europe 600 index. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Table 11
Country-specific determinants of electricity price volatility, aggregating all fossil fuels.

	Denmark		Estonia		Finland		France		Germany		Greece		Hungary		Italy		Norway		Poland		Spain		Sweden		Switzerland	
	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.	Est.	Std. E.
(Intercept)	2.94***	(0.06)	3.30***	(0.09)	3.22***	(0.06)	3.26***	(0.05)	3.21***	(0.04)	3.04***	(0.05)	3.44***	(0.06)	3.25***	(0.04)	1.69***	(0.05)	3.08***	(0.05)	2.73***	(0.06)	2.56***	(0.06)	2.91***	(0.05)
Non renewables	0.24***	(0.05)	0.04	(0.10)	0.63***	(0.10)	−0.17***	(0.04)	−0.17*	(0.08)	−0.27*	(0.11)	−0.22	(0.14)	−0.07	(0.20)	−0.20	(0.14)	−0.14	(0.19)	0.03	(0.08)	0.74***	(0.18)		
Nuclear					0.34	(0.27)	−0.68*	(0.33)	−0.83***	(0.21)			−0.24	(0.22)							−0.01	(0.20)	−0.13	(0.38)	−0.20.	(0.11)
Other renewables	0.02	(0.03)	−0.16*	(0.08)	0.26	(0.18)	0.24*	(0.12)	0.57**	(0.18)	0.20***	(0.04)	0.04	(0.08)	0.08	(0.14)	−0.01	(0.64)	−0.01	(0.06)	0.37***	(0.07)	0.04	(0.19)	−0.13	(0.09)
Solar	0.01	(0.02)	0.01	(0.02)	0.10	(0.14)	−0.01	(0.03)	0.05*	(0.02)	0.04	(0.03)	0.01	(0.02)	0.01	(0.03)			0.02	(0.03)	0.08***	(0.02)	0.04	(0.05)	0.01	(0.01)
Wind	0.02	(0.03)	−0.07***	(0.02)	−0.01	(0.02)	−0.05*	(0.02)	−0.09***	(0.02)	−0.01	(0.03)	0.00	(0.01)	−0.03	(0.02)	0.00	(0.04)	−0.13***	(0.02)	0.22***	(0.03)	−0.11*	(0.06)	−0.02**	(0.01)
EUA	−0.37	(0.61)	0.60	(0.53)	0.01	(0.62)	−0.15	(0.48)	0.36	(0.45)	0.16	(0.60)	0.62	(0.40)	0.20	(0.37)	0.42	(0.79)	0.38	(0.54)	−0.07	(0.43)	−0.43	(0.70)	−0.12	(0.43)
Gas price	0.04	(0.64)	0.11	(0.53)	−0.15	(0.63)	−0.24	(0.53)	−0.40	(0.63)	−0.09	(0.73)	−0.35	(0.47)	−0.3	(0.63)	−0.28	(0.79)	0.49	(0.55)	−0.16	(0.52)	−0.71	(0.93)	0.13	(0.65)
Oil price	0.73	(0.61)	0.76	(0.54)	−0.39	(0.64)	0.19	(0.47)	0.02	(0.49)	0.23	(0.63)	0.31	(0.42)	0.39	(0.43)	0.33	(0.87)	0.37	(0.51)	0.86.	(0.45)	−0.02	(0.95)	0.02	(0.50)
Coal price	0.27	(0.70)	0.18	(0.67)	0.79	(0.77)	0.17	(0.69)	0.18	(0.79)	−0.44	(0.89)	0.29	(0.65)	0.46	(0.73)	0.03	(1.09)	−0.22	(0.57)	−0.58	(0.71)	1.09	(1.11)	0.33	(0.75)
Country-specific load	1.42***	(0.38)	0.40	(0.30)	1.85***	(0.49)	0.63*	(0.26)	0.40	(0.36)	−0.44	(0.30)	0.16	(0.17)	0.45*	(0.19)	1.91**	(0.63)	0.45*	(0.20)	−0.02	(0.25)	1.16**	(0.43)	0.69**	(0.26)
Total load	0.11	(0.41)	0.94**	(0.32)	1.14**	(0.40)	0.50	(0.35)	0.32	(0.57)	0.25	(0.39)	0.43	(0.29)	−0.25	(0.37)	1.16**	(0.44)	0.13	(0.38)	0.33	(0.26)	1.61***	(0.47)	0.42	(0.30)
Stoxx	−1.91	(1.31)	−2.72*	(1.16)	−1.23	(1.50)	−1.13	(0.96)	−1.02	(1.11)	0.03	(1.38)	−0.87	(0.93)	−0.57	(1.01)	−1.48	(1.67)	−2.60*	(1.14)	−1.30	(0.89)	−0.44	(2.26)	−0.84	(1.13)
COVID	0.44***	(0.09)	0.56***	(0.11)	0.49***	(0.09)	−0.11	(0.09)	0.06	(0.06)	0.46***	(0.06)	−0.18*	(0.08)	−0.11.	(0.06)	−0.55*	(0.25)	−0.05	(0.07)	−0.02	(0.11)	0.58***	(0.10)	−0.03	(0.07)
Ukraine	1.57***	(0.11)	1.75***	(0.15)	1.18***	(0.17)	1.24***	(0.10)	1.55***	(0.10)	1.81***	(0.08)	1.28***	(0.10)	1.22***	(0.09)	1.65***	(0.11)	1.27***	(0.11)	1.38***	(0.08)	1.64***	(0.12)	1.22***	(0.09)

The table reports results from the OLS regressions on the country-specific electricity price volatility with Newey–West standard errors to correct for heteroscedasticity and autocorrelation for Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Norway, Poland, Spain, Sweden and Switzerland. Hereby, the fossil fuels, gas and coal are aggregated to the category non-renewables, including oil and waste. The standard errors are reported in brackets. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Table 12
Country-specific determinants of electricity price volatility, aggregating all fossil fuels.

	Est.	Std. E.
(Intercept)	3.07***	(0.13)
Non renewables	−0.02	(0.12)
Nuclear	−0.20	(0.15)
Other renewables	0.41***	(0.10)
Solar	0.05***	(0.01)
Wind	−0.01	(0.01)
EUA	0.02	(0.15)
Gas price	−0.32***	(0.08)
Oil price	0.16	(0.14)
Coal price	0.33	(0.22)
Country-specific load	0.56**	(0.20)
Total load	0.67***	(0.12)
Stoxx	−0.96***	(0.15)
COVID	0.14	(0.12)
Ukraine	1.38***	(0.07)

The table reports results from a panel regression on electricity price volatility with heteroscedasticity and serial correlation robust standard errors by Amemiya [38]. Hereby, the fossil fuels, gas and coal are aggregated to the category non-renewables, including oil and waste. Statistical significance is indicated by *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and . $p < 0.10$.

Data availability

Data will be made available on request.

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