INTERNATIONAL MONETARY FUND

Chasing the Sun and Catching the Wind: Energy Transition and Electricity Prices in Europe

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WP/22/220

2022
NOV

WORKING PAPER

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IMF Working Paper

European Department

Chasing the Sun and Catching the Wind: Energy Transition and Electricity Prices in Europe

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Authorized for distribution by Bernardin Akitoby

November 2022

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Abstract

European power markets are in the midst of unprecedented changes, with a record-breaking surge in energy prices.This paper investigates the impact of green power resources on the level and volatility of wholesale electricity prices at a granular level, using monthly observations for a panel of 24 European countries over the period 2014–2021 and alternative estimation methods including a panel quantile regression approach. We find that renewable energy is associated with a significant reduction in wholesale electricity prices in Europe, with an average impact of 0.6 percent for each 1 percentage points increase in renewable share. We also find evidence for a nonlinear effect—that is, higher the share of renewables, the greater its effect on electricity prices. On the other hand, while quantile estimation results are mixed with regards to the impact of renewables on the volatility of electricity prices, we obtain evidence that renewable energy has a negative effect on volatility at the highest quantiles. Overall, our analysis indicates that policy reforms can help accelerate the green transition while minimizing the volatility in electricity prices.

JEL Classification Numbers:	C21; C23; C34; Q41; Q42; Q48
Keywords:	Energy transition; renewables; electiricity prices; panel quantile regression; Europe
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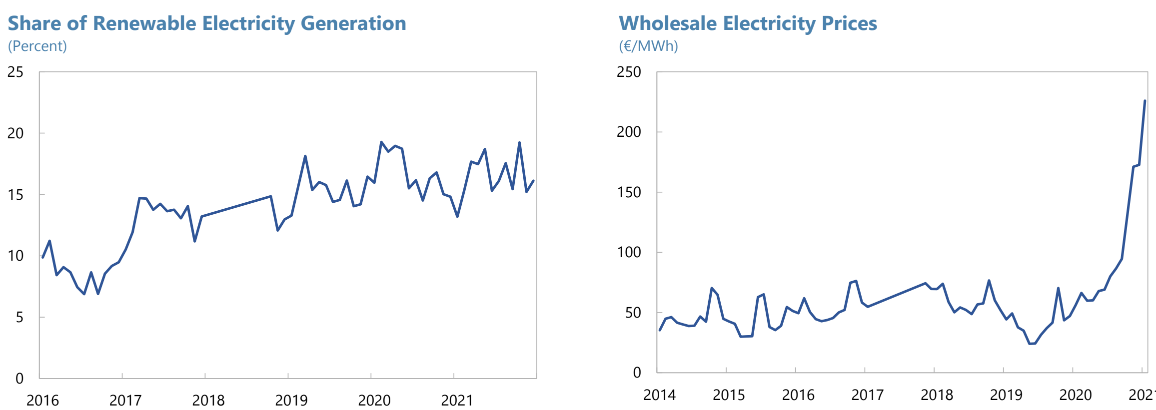
[1] The authors would like to thank Christian Bogmans, Borja Gracia, Andrea Pescatori, Axel Schimmelpfennig, Baoping Shang, Andrew Stanley, Zhongxia Zhang and the participants of a seminar at the European Department of the International Monetary Fund (IMF) for helpful comments and suggestions, and Sadhna Naik for excellent research assistance.

I. INTRODUCTION

A plethora of cyclical, structural and geopolitical developments has coalesced into a perfect storm in Europe with a record-breaking surge in energy prices. Russia's invasion of Ukraine has triggered the worst global energy crisis since the oil embargo of the 1970s, during a period of structural changes in the energy matrix as countries have been diversifying away from fossil fuels by increasing the share of renewable electricity generation in an effort to mitigate climate change.[2] Although the majority of electricity in Europe still comes from fossil fuels—accounting for about 42 percent as of 2021, the share of solar and wind has already reached 16.4 percent of total electricity generation. Higher penetration of renewables has significant benefits for decarbonization, but it is also a source of uncertainty on the intermittent and volatile production of renewable assets that could cause supply-demand imbalances, instability in the electricity grid, and more volatile pricing behavior (Figure 1). Therefore, as policymakers in Europe scramble to respond the energy crisis and shield consumers against higher energy prices, it is critical to better understand how renewable energy affects electricity prices.

European power markets are in the midst of unprecedented changes, with a tightening supply-and-demand balance. Wholesale electricity prices in Europe increased by more than 400 percent from an average of €35 per megawatt-hour (MWh) in 2020 to almost €250 per MWh in December 2021 even before the war in Ukraine, which pushed the average wholesale price of electricity above €500 per MWh in March 2022. Under the marginal pricing method underlying wholesale electricity prices in Europe, the most expensive technology needed to meet demand within a given period sets the final price of electricity according to the cost of production, which in turn depends on energy sources used in electricity generation. Therefore, in recent years, even

Figure 1. Energy Transition and Electricity Prices in Europe



Source: ENTSO-E; Eurostat; authors' calculations.

[2] Energy production is responsible for nearly three-quarters of global greenhouse gas emissions, with about half of these emissions coming from electricity generation alone.

as the levelized cost per unit of electricity from new utility-scale renewable power plants has dropped precipitously, the recent spike in wholesale electricity prices in Europe has broadly been driven by the cost of production at natural-gas power plants.

This study contributes to the debate by providing a panel data analysis how the green transition affects wholesale electricity prices in Europe. While the recent surge in oil and natural gas prices has certainly contributed to higher cost of electricity generation, the volatility of wholesale electricity prices depends on a broader set of factors including availability in generating units and intermittent output of renewables. The objective of this research is therefore twofold: (i) present stylized facts on the energy matrix and electricity markets across Europe; and (ii) explore the impact of solar and wind assets on the level and volatility of wholesale electricity prices. There is extensive literature on energy markets, but evidence on the role of renewables remains inconclusive. Some find a price-dampening impact of renewables (Sensfuß, Ragwitz, and Genoese, 2008; Würzburg, Labandeira, and Linares, 2013; Cludius and others, 2014; Ketterer, 2014; Clò, Cataldi, and Zoppoli, 2015; de Lagarde and Lantz, 2019; Maciejowska, 2020), but these studies focus on a single country using time-series data to analyze the merit-order effect that describes the decline in wholesale electricity prices due to an increase in the supply of renewable energy. In this context, a panel data approach can provide more accurate inference by accounting for both the time and cross-sectional dimensions of electricity prices in a large group of countries. To this end, we utilize monthly data on 24 European power markets during the period 2014–2021 and use alternative econometric methods including a panel quantile regression with fixed effects, which allow us to provide a granular analysis of the level and volatility of wholesale electricity prices and better capture nonlinearity effects of the green transition on various price quantiles in Europe.

The empirical analysis shows that renewable-based energy lowers the average level of wholesale electricity prices. As expected, renewable energy technologies with zero marginal costs have a statistically significant dampening effect on wholesale electricity prices in Europe during the period 2014–2021. The estimated coefficients on the share of solar and wind in total electricity generation imply that an increase of 1 percentage points in electricity produced by renewables lowers wholesale electricity prices by 0.6 percent on average. We also find evidence for a nonlinear effect—that is, higher the share of renewables, the greater its effect on wholesale electricity prices. Furthermore, the quantile regression approach—estimating the impact of solar and wind-based electricity generation on different quantiles of wholesale electricity prices—indicate that the share of renewables has a negative effect on the price level but at different magnitudes across the quantiles, especially when we conduct a more granular analysis by splitting the renewables into solar and wind. All in all, the price-dampening effect of renewables is economically significant and highly likely to be underestimated because of the relatively low share of renewables in the energy matrix—an average of 14 percent during the sample period.

We obtain mixed results with regards to the impact of intermittent renewable generation on the volatility of wholesale electricity prices. The standard analysis using the ordinary least squares (OLS) method shows that there is no statistically significant relationship between renewable electricity generation and the volatility of wholesale electricity prices, after controlling for total electricity load, crude oil import prices and average temperature. While the coefficient on the share of renewables is negative, the coefficient on its quadratic term is estimated to have a positive sign—an indication that higher the share of renewables, the greater its effect on the volatility of wholesale electricity prices. Furthermore, the quantile regression approach yields mixed results with regards to the impact of renewables on the volatility of electricity prices, but there is still some evidence that renewable energy has a dampening effect on price volatility at the highest quantiles. Nevertheless, the intermittent and volatile nature of electricity generation using renewable resources remains a concern as it may contribute to higher prices because of greater instability in electricity provision. Such uncertainty of electricity production could lead to higher electricity prices to compensate the risk premium incurred by the distribution companies.

Policy reforms can help accelerate the green transition in the energy matrix while minimizing the volatility in electricity prices. The transition to low-carbon sources of power generation is necessary for mitigating the socioeconomic consequences of climate change and strengthening energy security in Europe (Cevik, 2022). Based on our empirical findings, the green transition in the power sector could also help bring a significant reduction in electricity prices. For example, increasing the share of renewables in electricity production in Europe from an average level of 14 percent during the period 2014–2021 to 30 percent would lower wholesale electricity prices by 8.8 percent—and by almost 20 percent if the share of solar and wind reaches 50 percent. However, higher penetrations of renewable energy could also lead greater volatility in electricity production and thus higher wholesale prices. Therefore, to maximize the price dampening effect of green power resources, policymakers need to pursue reforms for modernization and closer integration of electricity grids throughout Europe and increase investment to reduce congestion on transmission lines and introduce volatility-dampening technology solutions like storage.

Building better electricity interconnections is necessary to increase cross-country electricity trade within Europe. This would improve the efficient allocation of electricity, especially considering the intermittent production of renewable sources. Especially in view of geostrategic challenges, Europe can benefit from a comprehensive continental electricity market established under the supervision of a multilateral mechanism for cross-country coordination with a mandate to harmonize energy policies and legal regulatory frameworks, identify strategic projects and secure necessary investments. In the current environment, to mitigate the direct impact of high energy prices caused by reduced crude oil and natural gas flows from Russia, targeted measures such as income support are better policies than an intervention in the wholesale market.[3] Last but not the least, our analysis strongly suggests that the intermittent and volatile production of renewable electricity requires countries to achieve a better balance between solar and wind and diversify the energy matrix with nonhydrocarbon and non-weather

[3] Higher wholesale electricity prices have put upward pressure on retail prices paid by households and commercial entities. The European Union has agreed on a package of energy emergency measures amounting to €376 billion to compensate consumers for the increase in electricity prices.

sensitive technologies like a new generation of geothermal and nuclear power plants taking a more prominent role in providing a stable and consistent stream of electricity across Europe.

The remainder of this paper is structured as follows. Section II provides an overview of the relevant literature. Section III presents the data used in the analysis and stylized facts on the energy matrix and electricity markets in Europe. Section IV presents the empirical methodology and results including a battery of robustness checks. Finally, Section VI offers concluding remarks with policy recommendations.

II. A Brief Overview of the Literature

Climate change has become the defining challenge of the 21st century, requiring far-reaching changes in the power sector. With the global surface temperature already increasing by about 1.1 degrees Celsius (°C) compared with the preindustrial average, the risk of extreme weather events—such as heat waves, wildfires, droughts, flooding, and severe storms—is projected to increase over the next century, as the global mean temperature continues to rise by as much as 4°C over the next century (IPCC 2007, 2014, 2019; 2021). Facing a narrow possibility to escape its worst environmental and socioeconomic consequences, countries are moving away from fossil fuels—the main source of carbon (CO_2) emissions—and investing in alternative sources of energy with smaller CO_2 footprint. The increase in renewable energy penetration can lead to a significant decline in CO_2 emissions, but it is also a source of uncertainty on the intermittent production of renewable assets that could cause supply-demand imbalances, greater instability in the electricity grid, and more volatile pricing behavior.

There is a bourgeoning literature on energy transition away from hydrocarbons and its impact on electricity prices. Investigating the relationship between renewables and electricity prices, some studies find that an increase in the share of renewable sources in the energy matrix is found to lower wholesale prices in a number of electricity markets (Sensfuß, Ragwitz, and Genoese, 2008; Gelabert, Labandeira, and Linares, 2011; Würzburg, Labandeira, and Linares, 2013; Cludius and others, 2014; Clò, Cataldi, and Zoppoli, 2015; Gullì and Balbo, 2015; Kyritsis, Andersson, and Serletis, 2017; de Lagarde and Lantz, 2019; Csereklyei, Qu, and Ancev, 2019; Prol, Steininger, and Zilberman, 2020). This negative impact, known as the merit-order effect in the literature, is attributed to the low marginal cost of renewables, which shifts the electricity supply curve to the right, thereby lowering the average price of electricity.

Another strand of these studies focuses on the relationship between renewable electricity generation and the volatility of electricity prices. As the share of renewable electricity generation has increased over time in many countries, studies look at the sharp fluctuations in pricing behavior caused by the intermittent nature of electricity generation through solar and wind. For example, Green and Vasilakos (2010), Woo and others (2011), Ketterer (2014), Ballester and Furió (2015), Clò, Cataldi, and Zoppoli (2015), Kyritsis, Andersson, and Serletis (2017), Martinez-Anido, Brinkman, and Hodge (2016), and Rintamäki, Siddiqui, and Salo (2017) show that an increase in the electricity supply from intermittent renewable assets, such as solar and wind, increases the volatility of wholesale electricity prices, even if there is a decline in the average level of price. This is mainly because of the unpredictability of renewable sources of energy and the inability to store electricity generated by renewables during periods of low demand when only a few conventional power plants can restrain production.

This paper builds on earlier studies but takes a different methodological approach to provide more robust cross-country estimates. Most of the literature focuses on time-series analysis of the relationship between renewable energy and electricity prices in a single country. A panel data approach, on the other hand, can improve the efficiency of econometric estimates and thereby provide more reliable inference of model parameters by taking into account both the time and cross-sectional dimensions, controlling for the impact of omitted variables, and uncovering dynamic relationships in a large sample of countries (Hsiao, Mountain, and Ho-Illman, 1995). Furthermore, as wholesale electricity prices are characterized by large fluctuations, spikes, and excess kurtosis, we use a panel quantile regression approach to present a granular investigation of the nonlinear effects of renewable energy on wholesale electricity prices at high frequency in a group of 24 European countries over the period 2014–2021.

III. DATA OVERVIEW AND STYLIZED FACTS

This paper uses a balanced panel dataset of monthly observations covering 24 countries in Europe during the period 2014–2021.[4] Wholesale electricity prices are obtained from the European Association for the Cooperation of Transmission System Operators (ENTSO-E) in €/MWh on a daily basis, which we convert to monthly averages. We measure the volatility of wholesale electricity prices as the standard deviation calculated from daily electricity prices ep_d and average monthly price $ep_m = \frac{1}{30}\sum_{d=1}^{30} ep_d$ in the following form:

$$v(ep_m) = \sqrt{\frac{1}{30}\sum_{d=1}^{30}(ep_d - ep_m)^2}$$

The main variable of interest is the share of electricity generated by renewable source, including solar and wind assets. We develop a more granular analysis by estimating the empirical model with the shares of solar and wind. We include total electricity load in gigawatt-hour (GWh)[5], monthly average crude oil import price in US$ per barrel, and monthly average temperature in degrees °C as control variables. The set of regressors including the main variables of interest is drawn from Eurostat. We take the logarithm of the level and volatility of wholesale electricity prices and all exogenous series (except temperature) to ensure stationarity and to

[4] The countries included in our sample are Austria, Belgium, Bulgaria, Croatia, the Czech Republic, Denmark, Estonia, Germany, Finland, France, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovenia, the Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom.

[5] As alternative, we include total electricity generating capacity (instead of total electricity load) and obtain similar results.

improve the model fit. This transformation into natural logarithm also allows the interpretation of coefficients as elasticities.

Summary statistics for electricity prices and renewable energy—the main variable of interest—show considerable heterogeneity across countries and over time. As displayed in Table 1, the mean value of wholesale electricity prices is €58.6 per MWh over the sample period, with a standard deviation of 75.4. Cross-country variation, for example, moves from a minimum of €1.4 per MWh in Norway to a maximum of €281 per MWh in Italy. The sample kurtosis is markedly higher than 3 for the level and volatility of wholesale electricity prices, indicating that distributions exhibit fat tails. Positive skewness, on the other hand, implies a greater probability of large increases in price and volatility than large declines. There is also significant seasonality in electricity prices, as shown in Figure 2. Seasonal variations, however, are highly correlated, and therefore it is sufficient to control for seasonality by including total electricity load and temperature in the model. The average volatility of wholesale electricity prices as measured by standard deviation is 21.3, albeit with significant variation across countries with a minimum of 0.3 and a maximum of 1,482. With regards to the main variable of interest, the share of renewables in total electricity generation varies from a minimum of 0 percent to a maximum of 78 percent, with a mean value of 14 percent during the sample period. While there is significant variation among European countries, there is a clear upward trend in electricity production using renewable technologies since the beginning of the 1990s, as shown in Table 2. On average, renewables accounted for 15.1 percent of total electricity generation in 2019, up from 0.02 percent in 1990. The breakdown of renewables also shows a similar pattern across countries and over time, with electricity generated by solar and wind increasing at an accelerating pace.

Table 1. Summary Statistics

Variable	Observations	Mean	Std. dev.	Skewness	Kurtosis	Minimum	Maximum
Wholesale electricity price	3,459	58.6	75.4	10.2	151.5	1.4	281.0
Volatility of wholesale electricity price	3,458	21.3	68.8	17.1	337.1	0.3	1,481.9
Renewable energy	3,459	1,827.6	2,117.7	2.9	15.7	0.0	22,519.0
Solar	2,902	689.6	1,067.3	1.8	4.0	0.0	7,831.0
Wind	3,459	1,142.3	1,427.1	5.1	41.2	0.0	20,681.0
Total electricity load	2,796	3,127,295	7,732,635	2.6	6.0	720.6	52,223,569
Crude oil import price	910	54.0	12.8	-0.1	-0.1	13.8	87.4
Temperature	2,332	10.2	7.9	0.1	-0.7	-11.4	26.9

Source: ENTSO-E; Eurostat; authors' calculations.

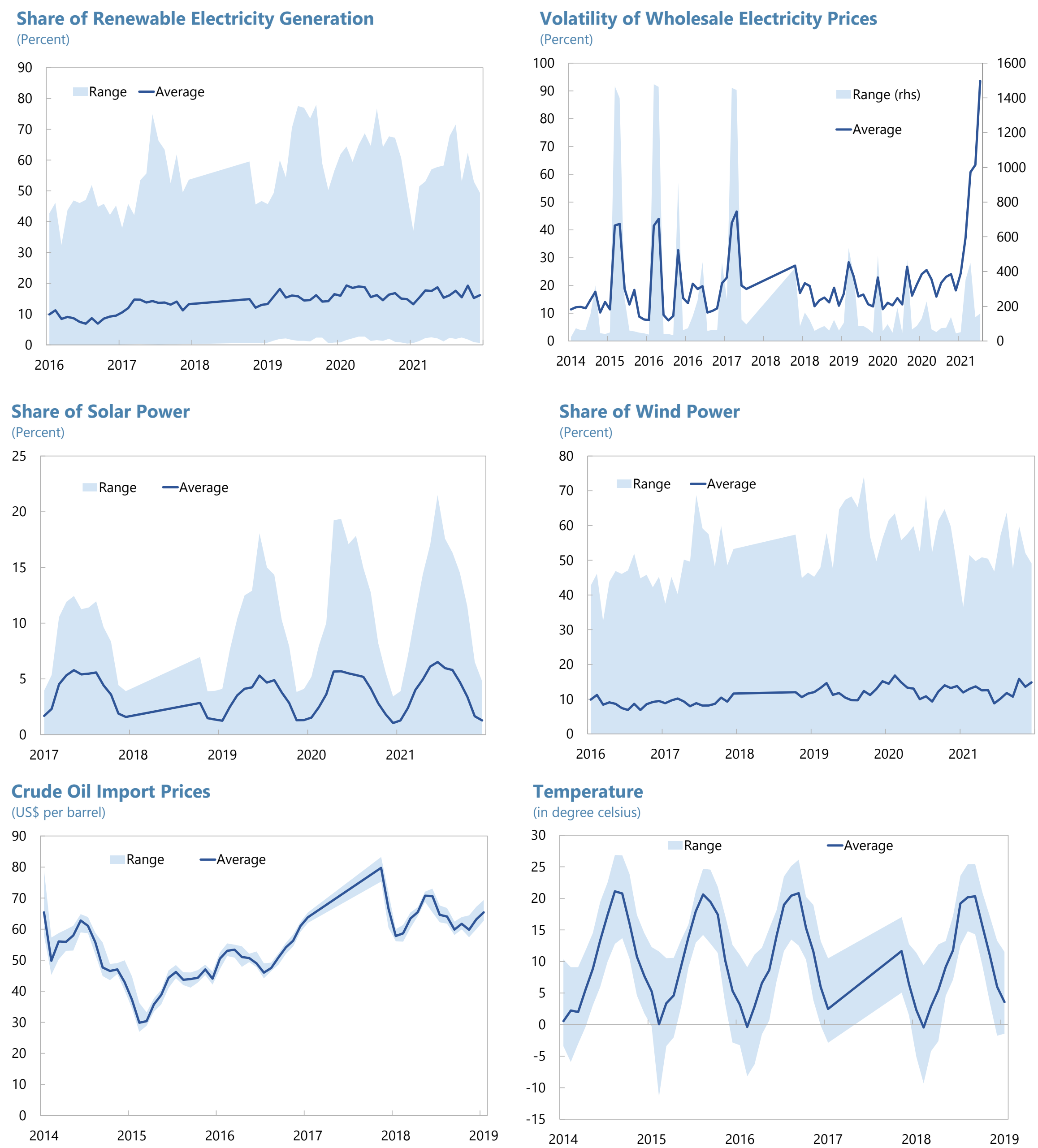
Table 2. Electricity Production by Technology

(Percent of total)

	Coal	Oil	Natural gas	Biofuels	Waste	Nuclear	Hydro	Geothermal	Solar	Wind	Others
1990	38.0	9.6	8.6	0.4	0.3	27.3	15.7	0.1	0.0	0.0	0.0
1995	33.6	8.0	10.3	0.5	0.4	29.4	17.5	0.1	0.0	0.1	0.0
2000	30.5	5.7	15.9	0.7	0.6	28.5	17.3	0.2	0.0	0.6	0.1
2005	28.9	3.9	20.3	1.5	0.7	27.5	15.0	0.2	0.0	1.8	0.3
2010	25.7	2.2	22.8	2.6	0.9	24.8	16.2	0.3	0.6	3.7	0.1
2015	25.4	1.7	16.7	3.9	1.1	23.7	16.3	0.4	2.7	7.8	0.2
2019	17.7	1.4	21.0	4.4	1.3	22.6	15.9	0.5	3.8	11.3	0.2

Source: International Energy Agency; authors' calculations.

Figure 2. Landscape of European Power Markets



Source: ENTSO-E; Eurostat; IMF; authors' calculations.
Note: Light blue area encompasses minimum and maximum observations.

Control variables used in the analysis present comparable variations across countries and over the sample period. The mean value of total electricity load is 3.1 million GWh over the sample period, with a minimum of 0.7 million GWh and a maximum of 52.2 million GWh. The average import price of crude oil is US$54 per barrel, with a minimum of US$13.8 per barrel and a maximum of US$84 per barrel. Finally, there is significant variation in monthly average temperature within Europe, varying from a minimum of -11.4 degrees °C and a maximum of 26.9

degrees °C with a mean value of 10.2 degrees °C. To avoid spurious estimation results, it is necessary to analyze the time-series properties of the data by conducting panel unit root tests. We check the stationarity of all variables by applying the Im-Pesaran-Shin (2003) procedure, which is widely used in the empirical literature. The results, available upon request, indicate that the variables are stationary after logarithmic transformation, and we can proceed with the analysis in log-levels without further modifications of the data.

IV. EMPIRICAL METHODOLOGY AND RESULTS

We empirically investigate the impact of energy transition on electricity prices in a panel of 24 countries in Europe over the period 2014–2021. Our analysis focuses on how higher penetrations of renewable energy affects the level and volatility of wholesale electricity prices. First, we explore the impact on the average level of wholesale electricity prices according to the following empirical specification estimated initially via the OLS approach:

$$ep_{i,t} = \alpha RE_{i,t} + \beta X_{i,t} + \eta_i + \mu_t + \varepsilon_{i,t}$$

where $ep_{i,t}$ denotes the logarithm of wholesale electricity prices in country i and time t; $RE_{i,t}$ is the share of renewable electricity generation (total, solar—thermal and photovoltaic—and wind—on-shore and off-shore); $X_{i,t}$ is a vector of control variables including the logarithm of total electricity load, monthly average crude oil import price, and monthly average temperature. Second, we estimate the impact on the volatility of wholesale electricity prices according to the following specification:

$$v(ep_{i,t}) = \alpha RE_{i,t} + \beta X_{i,t} + \eta_i + \mu_t + \varepsilon_{i,t}$$

where $v(ep_{i,t})$ denotes the logarithm of the standard deviation of wholesale electricity prices in country i and time t; $RE_{i,t}$ is the share of renewables (total, solar—thermal and photovoltaic—and wind—on-shore and off-shore) in total electricity generation; $X_{i,t}$ is a vector of control variables including the logarithm of total electricity load, monthly average crude oil import price, and monthly average temperature. In both equations, the η_i and μ_t coefficients denote the time-invariant country-specific effects and the time effects controlling for common shocks that may affect wholesale electricity prices across all countries in a given month, respectively. $\varepsilon_{i,t}$ is the idiosyncratic error term. To account for possible heteroskedasticity, robust standard errors are clustered at the country level.

To obtain a more granular analysis, we estimate these models using a panel quantile regression approach. The standard OLS regression considers only the conditional mean, thus concealing interesting characteristics and valuable information for certain parts of the conditional distribution of the level (or volatility) of wholesale electricity prices. Alternatively, the quantile regression approach, introduced by Koenker and Bassett (1978), quantifies the relationship of explanatory factors and each quantile of the conditional distribution. Therefore, it models the conditional quantile functions, instead of the mean in the standard regression analysis, and deals with nonlinearities and deviations from normality in the distribution of data. This helps provide robust estimates even in the presence of outliers and unobserved heterogeneity. In this paper, we follow Canay (2011) and implement the panel quantile regression approach with fixed effects:

$$p_{i,t,\tau} = \theta_\tau + \phi_\tau RE_{i,t} + \gamma_\tau X_{i,t} + \eta_i + \mu_t + \varepsilon_{i,t,\tau}$$

where $p_{it\tau}$ denotes the level (or volatility) of wholesale electricity prices in country i and time t at quantile τ (e.g., 10th percentile) conditional on the share of renewables in total electricity generation and the abovementioned control variables. The estimation procedure proposed by Canay (2011) includes two steps: (i) running a fixed-effects model to obtain the conditional mean of the residual; and (ii) estimating a quantile regression on the adjusted dependent variable, calculated from the original dependent variable subtracted from the conditional mean of the residual. As suggested by Angrist and Pischke (2009), we use the bootstrap clustered by group standard errors to treat potential heteroskedasticity and serial correlation in the panel.

Table 3. Energy Transition and Electricity Prices: OLS Estimations

	Level		Volatility	
	[1]	[2]	[1]	[2]
Renewables	-0.183***	-0.500***	-0.060	-0.055
	[0.042]	[0.132]	[0.066]	[0.211]
Renewables^2		-0.050*		0.001
		[0.020]		[0.032]
Load	0.875***	0.810***	0.630	0.631
	[0.222]	[0.222]	[0.351]	[0.354]
Crude oil price	0.476	0.483	0.168	0.167
	[0.452]	[0.449]	[0.717]	[0.718]
Temperature	0.024***	0.022***	0.028**	0.028**
	[0.006]	[0.006]	[0.009]	[0.009]
Number of observations	486	486	486	486
Number of countries	24	24	24	24
Country FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Adj R^2	0.85	0.85	0.76	0.76

Note: The dependent variable is the level or volatility of wholesale electricity prices. Robust standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

The green transition away from fossil fuels in electricity generation reduces the level of wholesale electricity prices. The estimation results, presented in Table 2, indicate a strong fit of the model to the panel dataset covering 24 countries in Europe during the period 2014–2021, with the expected signs across all specifications. The elasticity of wholesale electricity prices with respect to the share of renewables in total electricity generation is negative and statistically significant at the 1 percent level, after controlling for total electricity load, crude oil import prices and average temperature. These results confirm that an increase in the share of renewable energy is associated with a decline in wholesale electricity prices in Europe. Numerically, an increase of 1 percentage point in electricity produced by renewables is estimated to lower the level of wholesale electricity prices by about 0.6 percent on average. We also find evidence for a nonlinear effect by adding the quadratic term of renewable share. That is, higher the share of renewables, the greater its effect on wholesale electricity prices. As a result, the total impact of an additional 1 percentage point of renewable share on wholesale electricity prices would increase to 0.6 percent on average. In other words, raising the share of renewables in electricity production in Europe from an average 14 percent to 30 percent would lower wholesale electricity prices by 8.8 percent—and by almost 20 percent if the share of solar and wind reaches 50 percent. In our view, these estimates should be taken as a lower bound because of the low share of renewables during the sample period 2014–2021.

We obtain mixed results with regards to the impact of renewable electricity generation on the volatility of wholesale electricity prices. The standard OLS analysis, displayed in Table 3, indicates no statistically significant relationship between renewable-based electricity generation and price volatility as measured by the standard deviation of wholesale electricity prices, after controlling for total electricity load, crude oil import prices and average temperature. While the coefficient on renewable share is negative, the coefficient on its quadratic term has a positive sign. Albeit statistically insignificant at conventional levels, this is an indication that higher the

Table 4. Energy Transition and Electricity Prices: Quantile Estimations

	Level of Wholesale Electiricty Prices								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Renewables	-0.016	-0.068	-0.084	-0.056	-0.058	-0.223**	-0.526***	-0.840*	-1.157*
	[0.064]	[0.061]	[0.064]	[0.077]	[0.087]	[0.078]	[0.104]	[0.386]	[0.486]
Renewables^2	-0.004	-0.008	-0.014	-0.007	-0.016	-0.044**	-0.099***	-0.155*	-0.234**
	[0.012]	[0.012]	[0.013]	[0.013]	[0.016]	[0.014]	[0.018]	[0.072]	[0.080]
Load	0.011	0.020	0.019	0.025	0.026	0.023	0.011	0.023	0.017
	[0.012]	[0.012]	[0.011]	[0.018]	[0.020]	[0.016]	[0.024]	[0.083]	[0.078]
Crude oil price	0.528***	0.473***	0.535***	0.613***	0.632***	0.701***	0.785***	0.622*	1.115**
	[0.044]	[0.041]	[0.037]	[0.066]	[0.077]	[0.058]	[0.118]	[0.298]	[0.363]
Temperature	-0.001	0.000	0.000	-0.001	-0.002	-0.002	-0.007*	-0.01	-0.01
	[0.001]	[0.001]	[0.001]	[0.002]	[0.002]	[0.003]	[0.003]	[0.010]	[0.010]
Number of observations	486	486	486	486	486	486	486	486	486
Number of countries	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is the level of wholesale electricity prices. Bootstrapped standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

share of intermittent renewable generation, the greater its effect on the volatility of wholesale electricity prices. Although these mixed results may reflect data aggregation at the monthly frequency, they are nevertheless broadly in line with earlier studies that reached similarly mixed findings (Green and Vasilakos, 2010; Wozabal, Graf, and Hirschmann, 2016; Kyritsis, Andersson, and Serletis, 2017; Rintamäki, Siddiqui, and Salo, 2017).

The impact of renewable electricity production varies across the quantiles of wholesale electricity prices. Estimating the impact of renewable-based electricity generation on different quantiles of wholesale electricity prices, we find that the share of renewables has a negative effect on the price level but at different magnitudes across the quantiles. We use thresholds ranging from 0.1 to 0.9 to ensure the sufficient number of observation in each state and capture the pricing behavior across a broad spectrum. As presented in Table 4, we observe significant difference in the magnitude of the price-dampening effect of renewable-based electricity generation—ranging from -0.02 (including the quadratic term) at the 10^{th} quantile to -0.07 at the median quantile and -1.40 at the 90^{th} quantile. In other words, the estimated coefficient becomes larger at the highest quantiles than the median and lowest quantiles, indicating that renewables have a stronger effect at the extreme end of the price distribution. This finding also suggests that increasing the share of renewables would be even more effective in lowering wholesale electricity prices in countries with relatively higher levels of prices due to the higher cost of production. The quantile regression analysis also yields interesting results with regards to the impact of renewable share on the volatility of wholesale electricity prices. As presented in Table 5, the estimated coefficient varies substantially across the quantiles in terms of sign, magnitude and statistical significance. Renewable-based electricity generation appears to have a dampening effect on price volatility at the at the highest quantiles than the median and lowest quantiles.

Table 5. Energy Transition and Volatility of Electricity Prices: Quantile Estimations

	Volatility of Wholesale Electiricty Prices								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Renewables	-0.006	0.084	0.099	0.054	-0.049	-0.205*	-0.543***	-0.875*	-1.164*
	[0.063]	[0.073]	[0.072]	[0.065]	[0.082]	[0.089]	[0.120]	[0.385]	[0.502]
Renewables^2	-0.004	0.01	0.015	0.005	-0.015	-0.042**	-0.103***	-0.161*	-0.237**
	[0.012]	[0.014]	[0.014]	[0.010]	[0.014]	[0.015]	[0.022]	[0.070]	[0.083]
Load	0.009	0.016	0.017	0.022	0.024	0.024	0.008	0.013	0.021
	[0.013]	[0.013]	[0.013]	[0.018]	[0.021]	[0.021]	[0.022]	[0.081]	[0.083]
Crude oil price	0.545***	0.507***	0.561***	0.636***	0.657***	0.737***	0.820***	0.660*	1.128**
	[0.048]	[0.035]	[0.047]	[0.071]	[0.075]	[0.080]	[0.119]	[0.298]	[0.377]
Temperature	0.000	0.001	0.000	-0.001	-0.002	-0.002	-0.007*	-0.010	-0.009
	[0.001]	[0.001]	[0.001]	[0.002]	[0.002]	[0.003]	[0.003]	[0.010]	[0.010]
Number of observations	486	486	486	486	486	486	486	486	486
Number of countries	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is the volatility of wholesale electricity prices. Bootstrapped standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

Conducting a granular analysis, we find substantially different impact functions for generation technologies. Since the mix of renewable assets in electricity generation is an important consideration for policymakers as well as investors, we divide the share of renewables into solar and wind to investigate how different generation technologies affect the level and volatility of wholesale electricity prices. These results, presented in Appendix Table A1, show that(i) solar-based electricity generation is more effective in lowering the level of wholesale electricity prices than wind power, after controlling for other factors; and (ii) solar power is associated with a reduction in the volatility of wholesale electricity prices, whereas wind power has a positive—and statistically insignificant—effect. This segregated picture remains when we use the quantile regression approach. According to results presented in Appendix Table A2-A5, the magnitude and statistical significance of the coefficients show substantial variation across the quantiles of wholesale electricity prices and different generation technologies but confirms that solar power tends to a stronger dampening effect on the level and volatility of wholesale electricity prices than wind-based electricity generation.

V. Conclusion

Europe's electricity markets are going through unprecedented changes driven by the energy transition and geopolitical tensions. The energy sector has long been in the midst of a structural shift away from fossil fuels in an effort to mitigate climate change, but geopolitical shock waves triggered by the war in Ukraine have coalesced into the worst global energy crisis since the oil embargo of the 1970s. Wholesale electricity prices in Europe increased from an average of €35 per MWh in 2020 to above €500 per MWh in March 2022, causing economic and political repercussions throughout the continent. Like commodity markets, electricity prices are set at the margin. In other words, the most expensive technology needed to meet demand within a given period sets the wholesale electricity price. In recent years—and especially now, electricity prices in Europe are determined by the import price of natural gas. At the same time, while higher penetration of renewable energy has significant benefits for decarbonization, it is also a source of significant uncertainty on the intermittent and volatile production of renewable assets that cause supply-demand imbalances, greater instability in the electricity grid, and more volatile pricing behavior.

This study contributes to the debate by providing a panel data analysis how the green transition affects wholesale electricity prices in Europe. While the recent surge in crude oil and natural gas prices has certainly contributed to higher cost of electricity generation, the volatility of wholesale electricity prices depends on a broader set of factors including availability in generating units and intermittent output of renewables. There is extensive literature on energy markets, but evidence on the role of renewables remains inconclusive. Some find a price-dampening impact of renewables, but these studies focus on a single country using time-series analysis. In this context, a panel data approach can provide more accurate inference of model parameters by accounting for both the time and cross-sectional dimensions of electricity prices in a large group of countries. To this end, we utilize monthly data on 24 European power markets during the period 2014–2021 and use alternative econometric methods including a panel quantile regression approach, which allow us to provide a granular analysis of the level and volatility of wholesale electricity prices and better capture nonlinearity effects of the green transition on various price quantiles in Europe.

The empirical analysis shows that renewable-based energy lowers the average level of wholesale electricity prices. As expected, renewable energy technologies with zero marginal costs have a statistically significant dampening effect on wholesale electricity prices in Europe during the period 2014–2021. The estimated coefficient on the share of renewables in total electricity generation implies that an increase of 1 percentage points in electricity produced by renewables lowers wholesale electricity prices by 0.6 percent on average. We also find evidence for a nonlinear effect—that is, higher the share of renewables, the greater its effect on wholesale electricity prices. Furthermore, the quantile regression approach—estimating the impact of renewable-based electricity generation on different quantiles of wholesale electricity prices—indicate that the share of renewables has a negative effect on the price level but at different magnitudes across the quantiles, especially when we conduct a more granular analysis by splitting the renewables into solar and wind. All in all, the price-dampening effect of renewables is economically significant and highly likely to be underestimated because of the relatively low share of renewables in the energy matrix—an average of 14 percent during the sample period.

There are mixed results with regards to the impact of intermittent renewable generation on the volatility of wholesale electricity prices. The standard analysis shows no statistically significant relationship between renewable electricity generation and price volatility in Europe during the sample period, after controlling for total electricity load, crude oil import prices and average temperature. While the coefficient on the share of renewables is negative, the coefficient on its quadratic term is estimated to have a positive sign—an indication that higher the share of renewables, the greater its effect on the volatility of wholesale electricity prices. Furthermore, the quantile regression approach yields mixed results with regards to the impact of renewables on the volatility of electricity prices, but there is still some evidence that renewable energy has a dampening effect on price volatility at the highest quantiles. Nevertheless, the intermittent and volatile nature of electricity generation using renewable resources remains a concern as it may contribute to higher prices because of greater instability in electricity provision. Such uncertainty of electricity production could lead to higher electricity prices to compensate the risk premium incurred by the distribution companies.

Policy reforms can help accelerate the green transition in the energy matrix while minimizing the volatility in electricity prices. The transition to low-carbon sources of power generation is necessary for mitigating the socioeconomic consequences of climate change and strengthening energy security in Europe (Cevik, 2022). As shown by our empirical analysis, the green transition in the power sector could also help bring a significant reduction in electricity prices. For example, increasing the share of renewables in electricity production in Europe from an average level of 14 percent during the period 2014–2021 to 30 percent would lower wholesale electricity prices by 8.8 percent—and by almost 20 percent if the share of solar and wind reaches 50 percent. However, higher penetrations of renewable energy could also lead greater volatility in electricity production and thus higher wholesale prices. Therefore, to maximize the price dampening effect of green power resources, policymakers need to pursue reforms for modernization and closer integration of electricity grids throughout Europe and increase investment to reduce congestion on transmission lines and introduce volatility-dampening technology solutions like storage.

Building better electricity interconnections is necessary to increase cross-country electricity trade within Europe. This would improve the efficient allocation of electricity, especially considering the intermittent and volatile production of renewable sources. Especially in view of geostrategic challenges, Europe can benefit from a comprehensive continental electricity market established under the supervision of a multilateral mechanism for cross-country coordination with a mandate to harmonize energy policies and legal regulatory frameworks, identify strategic projects and secure necessary investments. In the current environment, to mitigate the impact of high energy prices, targeted measures such as income support are better policies than an intervention in the wholesale market. Last but not the least, our analysis strongly suggests the intermittent and volatile production of renewables requires countries to achieve a better balance between the solar and wind power and diversify the energy matrix with nonhydrocarbon and non-weather sensitive technologies like a new generation of geothermal and nuclear power plants taking a more prominent role in providing a stable and consistent stream of electricity across Europe.

Appendix Table A1. Renewable Technologies and Electricity Prices: OLS Estimations

	Level						Volatility					
	[1]	[2]	[3]	[4]	[5]	[6]	[1]	[2]	[3]	[4]	[5]	[6]
Renewables	-0.183***	-0.500***					-0.060	-0.055				
	[0.042]	[0.132]					[0.006]	[0.211]				
$Renewables^2$		-0.050*						0.001				
		[0.020]						[0.032]				
Solar			0.067*	-0.323***					-0.156***	-0.356**		
			[0.027]	[0.066]					[0.045]	[0.113]		
$Solar^2$				-0.033***						-0.043***		
				[0.005]						[0.009]		
Wind					-0.142*	-0.276					0.070	0.208
					[0.056]	[0.156]					[0.088]	[0.242]
$Wind^2$						-0.024						0.025
						[0.026]						[0.041]
Load	0.457***	0.810***	0.861***	1.151***	1.036***	1.151***	0.630	0.631	0.687	0.697	0.644	0.795*
	[0.082]	[0.222]	[0.232]	[0.210]	[0.223]	[0.210]	[0.351]	[0.354]	[0.361]	[0.362]	[0.373]	[0.360]
Temperature	0.010**	0.022***	0.021***	0.021***	0.022***	0.021***	0.028**	0.028**	0.029**	0.028**	0.024*	0.023*
	[0.003]	[0.006]	[0.006]	[0.006]	[0.006]	[0.006]	[0.009]	[0.009]	[0.010]	[0.010]	[0.010]	[0.010]
Crude oil price	0.476	0.483	0.437	0.984	0.452	0.984	0.168	0.167	0.019	0.016	0.046	0.744
	[0.452]	[0.449]	[0.484]	[0.568]	[0.600]	[0.568]	[0.717]	[0.718]	[0.754]	[0.755]	[1.002]	[0.973]
Number of observations	486	486	465	465	323	323	486	486	465	465	323	323
Number of countries	24	24	24	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj R^2	0.85	0.85	0.84	0.84	0.90	0.91	0.76	0.76	0.76	0.76	0.84	0.85

Note: The dependent variable is the level or volatility of wholesale electricity prices. Robust standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

Appendix Table A2. Solar Power and Electricity Prices: Quantile Estimations

	Level of Wholesale Electiricty Prices								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Solar	-0.047	-0.149***	-0.200**	-0.244***	-0.322***	-0.345*	-0.396	-0.690	0.126
	[0.059]	[0.034]	[0.070]	[0.069]	[0.075]	[0.149]	[0.266]	[0.386]	[0.308]
$Solar^2$	-0.006	-0.014***	-0.018**	-0.023***	-0.030***	-0.032	-0.032	-0.045	-0.001
	[0.005]	[0.003]	[0.006]	[0.006]	[0.007]	[0.017]	[0.027]	[0.032]	[0.027]
Load	0.020	0.008	0.023	0.051**	0.058**	0.051	0.066	0.026	0.522***
	[0.014]	[0.010]	[0.016]	[0.019]	[0.020]	[0.030]	[0.053]	[0.099]	[0.078]
Crude oil price	0.246*	0.395***	0.474***	0.439***	0.464***	0.328	0.237	0.543	0.689*
	[0.104]	[0.064]	[0.101]	[0.120]	[0.138]	[0.177]	[0.355]	[0.633]	[0.319]
Temperature	-0.001	0.003**	0.003	0.001	0.002	0.001	0.005	0.019	-0.008
	[0.002]	[0.001]	[0.003]	[0.003]	[0.003]	[0.005]	[0.009]	[0.012]	[0.010]
Number of observations	465	465	465	465	465	465	465	465	465
Number of countries	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is the level of wholesale electricity prices. Bootstrapped standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

Appendix Table A3. Wind Power and Electricity Prices: Quantile Estimations

	Level of Wholesale Electiricty Prices								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Wind	-0.017	0.007	0.041	0.033	-0.022	-0.091	-0.232	-0.339	0.317
	[0.030]	[0.028]	[0.030]	[0.051]	[0.057]	[0.667]	[0.902]	[0.220]	[0.223]
$Wind^2$	-0.002	0.001	0.004	0.002	-0.002	-0.011	-0.029	-0.045	0.014
	[0.004]	[0.004]	[0.004]	[0.008]	[0.007]	[0.144]	[0.192]	[0.023]	[0.024]
Load	0.006	0.003	0.017	0.023	0.017	0.019	0.002	0.017	0.132
	[0.009]	[0.013]	[0.013]	[0.017]	[0.021]	[0.060]	[0.069]	[0.108]	[0.095]
Crude oil price	0.549***	0.506***	0.533***	0.618***	0.687***	0.709***	0.783***	0.887**	0.953*
	[0.030]	[0.044]	[0.044]	[0.066]	[0.076]	[0.092]	[0.127]	[0.314]	[0.403]
Temperature	-0.001	0.001	0.000	-0.001	-0.003	-0.002	-0.002	-0.006	0.006
	[0.001]	[0.001]	[0.001]	[0.002]	[0.002]	[0.003]	[0.004]	[0.010]	[0.010]
Number of observations	323	323	323	323	323	323	323	323	323
Number of countries	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is the level of wholesale electricity prices. Bootstrapped standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

Appendix Table A4. Solar Power and Electricity Price Volatility: Quantile Estimations

	Volatility of Wholesale Electiricty Prices								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Solar	-0.053	-0.161***	-0.212**	-0.274***	-0.348***	-0.368*	-0.417	-0.714	0.128
	[0.066]	[0.043]	[0.077]	[0.072]	[0.084]	[0.172]	[0.274]	[0.396]	[0.315]
$Solar^2$	-0.007	-0.015***	-0.020**	-0.026***	-0.032***	-0.035	-0.033	-0.046	-0.002
	[0.006]	[0.004]	[0.007]	[0.006]	[0.007]	[0.019]	[0.028]	[0.033]	[0.028]
Load	0.015	0.001	0.015	0.045*	0.059**	0.049	0.063	0.024	0.531***
	[0.015]	[0.010]	[0.018]	[0.021]	[0.022]	[0.032]	[0.053]	[0.127]	[0.076]
Crude oil price	0.255*	0.403***	0.498***	0.476***	0.473**	0.326	0.223	0.563	0.699*
	[0.113]	[0.073]	[0.112]	[0.129]	[0.148]	[0.205]	[0.361]	[0.647]	[0.325]
Temperature	-0.001	0.004*	0.003	0.001	0.003	0.001	0.006	0.019	-0.008
	[0.003]	[0.002]	[0.003]	[0.003]	[0.004]	[0.006]	[0.009]	[0.013]	[0.010]
Number of observations	465	465	465	465	465	465	465	465	465
Number of countries	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is the volatility of wholesale electricity prices. Bootstrapped standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

Appendix Table A5. Wind Power and Electricity Price Volatility: Quantile Estimations

	Volatility of Wholesale Electiricty Prices								
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Wind	0.006	0.013	0.067*	0.057	0.000	-0.089	-0.221	-0.330	0.328
	[0.030]	[0.031]	[0.033]	[0.057]	[0.059]	[0.713]	[0.934]	[0.229]	[0.228]
$Wind^2$	0.001	0.001	0.007	0.005	0.001	-0.011	-0.028	-0.044	0.014
	[0.004]	[0.004]	[0.004]	[0.008]	[0.008]	[0.153]	[0.197]	[0.024]	[0.025]
Load	0.005	0.003	0.017	0.026	0.022	0.016	0.003	0.015	0.130
	[0.010]	[0.014]	[0.015]	[0.019]	[0.022]	[0.064]	[0.075]	[0.112]	[0.099]
Crude oil price	0.564***	0.530***	0.575***	0.647***	0.696***	0.744***	0.830***	0.932**	1.002*
	[0.034]	[0.049]	[0.048]	[0.075]	[0.080]	[0.103]	[0.132]	[0.346]	[0.419]
Temperature	0.000	0.001	0.001	-0.001	-0.003	-0.001	-0.002	-0.006	0.006
	[0.001]	[0.001]	[0.001]	[0.002]	[0.003]	[0.003]	[0.005]	[0.010]	[0.011]
Number of observations	323	323	323	323	323	323	323	323	323
Number of countries	24	24	24	24	24	24	24	24	24
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is the volatility of wholesale electricity prices. Bootstrapped standard errors clustered at the country level are reported in brackets. A constant is included in each regression, but not shown in the table. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Source: Authors' estimations.

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