High electricity price despite expansion in renewables: How market trends shape Germany's power market in the near future

Mario Liebensteiner[a] Fabian Ocker[b] Anas Abuzayed[c]

September 2024

Abstract: Expectations about future energy prices are crucial for investment decisions, market reform debates, and public policy. Yet, the recent energy crisis caused dramatic market uncertainty. This study investigates Germany's near-future electricity price in the context of evolving market trends. A flexible econometric model is applied to high-frequency, near-time data, spanning January 2015 through May 2023. A potential endogeneity bias of trade is circumvented by an instrumental-variables approach. Results indicate that expanding renewable energy exerts downward pressure on price, countering trends like the nuclear phaseout, a rising carbon price, increased electrification, and a high gas price. The collective impact suggests a considerably higher electricity price in the coming years compared to pre-crisis levels. This finding is corroborated by a fundamental energy system model. The potential rise in renewables' production volatility may amplify electricity price volatility. A high and volatile near-future electricity price could spur investments in renewables and flexibility technologies but pose challenges for consumers. Our analysis aids evidence-based decision-making amid the post-crisis landscape.

Keywords: electricity price; market trends; price prediction; renewable energy

Acknowledgments: The work on the energy system model MyPyPSA-Ger was carried out as part of the project GaIN - Gewinnbringende Partizipation der mittelständischen Industrie am Energiemarkt der Zukunft; FKZ 0EI6019E, BMWi 2019–2022. A.A. gratefully acknowledges the German Federal Ministry of Economics and Technology (BMWi) for their funding.

Competing interests statement: The authors declare no competing interests.

[a] Corresponding author. Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg, Institute of Economic Research, Germany, mario.liebensteiner@fau.de

[b] TenneT TSO GmbH, Germany, fabian.ocker@tennet.eu

[c] Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg, Institute of Economic Research, and Offenburg University of Applied Sciences, Institute of Sustainable Energy Systems, Germany, anas.abuzayed@hs-offenburg.de

1 Introduction

Expectations about the future electricity price are of paramount relevance (Baratsas et al., 2021). They determine investment decisions regarding generation capacities and flexibility enabling technologies, influence the deployment of electric vehicles, shape strategic political actions and public policy (e.g., on the optimal support level of renewable energies), have allocative consequences, and influence discussions about the design of the future electricity market. However, the decarbonization transition and the recent energy crisis have caused severe turmoil at European energy markets. Figure 1 shows that European energy prices exhibited unprecedented volatility since about mid 2021, skyrocketing in August 2022, followed by a significant recovery. This raises the question about which electricity price level and volatility we can expect in the coming years.

The widespread perception of a future electricity system is that it will be fed mainly by renewable energies, with wind and solar power as the dominant technologies (Thimet and Mavromatidis, 2022; Sasse and Trutnevyte, 2020), and backed by complementary flexibility-enabling measures, including the expansion of networks and interconnectors, deployment of dispatchable low-carbon generation units (such as combined-cycle gas turbines with carbon capture and storage), utilization of demand-side flexibility (e.g., through smart metering and flexible contracts), and implementation of energy storage solutions (Newbery et al., 2018; Palzer and Henning, 2014).

Studies have shown that a rising share of renewables decreases the average electricity price (known as the "merit-order effect"; Bushnell and Novan, 2021; Clo et al., 2015; Csereklyei et al., 2019; Maciejowska, 2020; Welisch et al., 2016), leads to an increasing number of hours with low or even negative prices (Biber et al., 2022; De Vos, 2015; Liebensteiner and Naumann, 2022), and cannibalizes renewables' own market values (the revenues that renewables can generate when they feed into the system; Hirth, 2013; Liebensteiner and Naumann, 2022; Lòpez Prol et al., 2021). Expectations of, on average, low and frequently negative electricity prices have caused scholars and politicians to question the current market design (Bublitz et al., 2019; Frew et al., 2023; Hu et al., 2018; Sasse and Trutnevyte, 2020; Silva-Rodriguez et al., 2022; Xiang et al., 2023). Yet, it has been shown that higher gas and CO_2 allowance prices and more electricity demand can counteract a falling electricity price (Liebensteiner and Naumann, 2022; Liebensteiner et al., 2023; Kosch et al., 2023).

Germany stands out as an interesting case study due to its high share of renewable energies (49% in gross electricity supply in 2022), ambitious targets to increase this share to 80% by 2030 (Bundesregierung, 2022), and recent influential political decisions, such as the phaseout of nuclear power and the electrification of other economic sectors, foremost mobility and space heating. Moreover, Germany's power sector is covered by the EU Emission Trading System (EU ETS), with a soaring CO_2 allowance price during the last years. Germany's electricity sector is also interesting to study, because it is located in the heart of Europe and lays the foundation for economic development. The aim of this study is to develop an understanding of how major market trends may shape Germany's electricity price during the coming years and to draw policy lessons.

We apply high-frequency (hourly and daily), publicly available data to model the variation

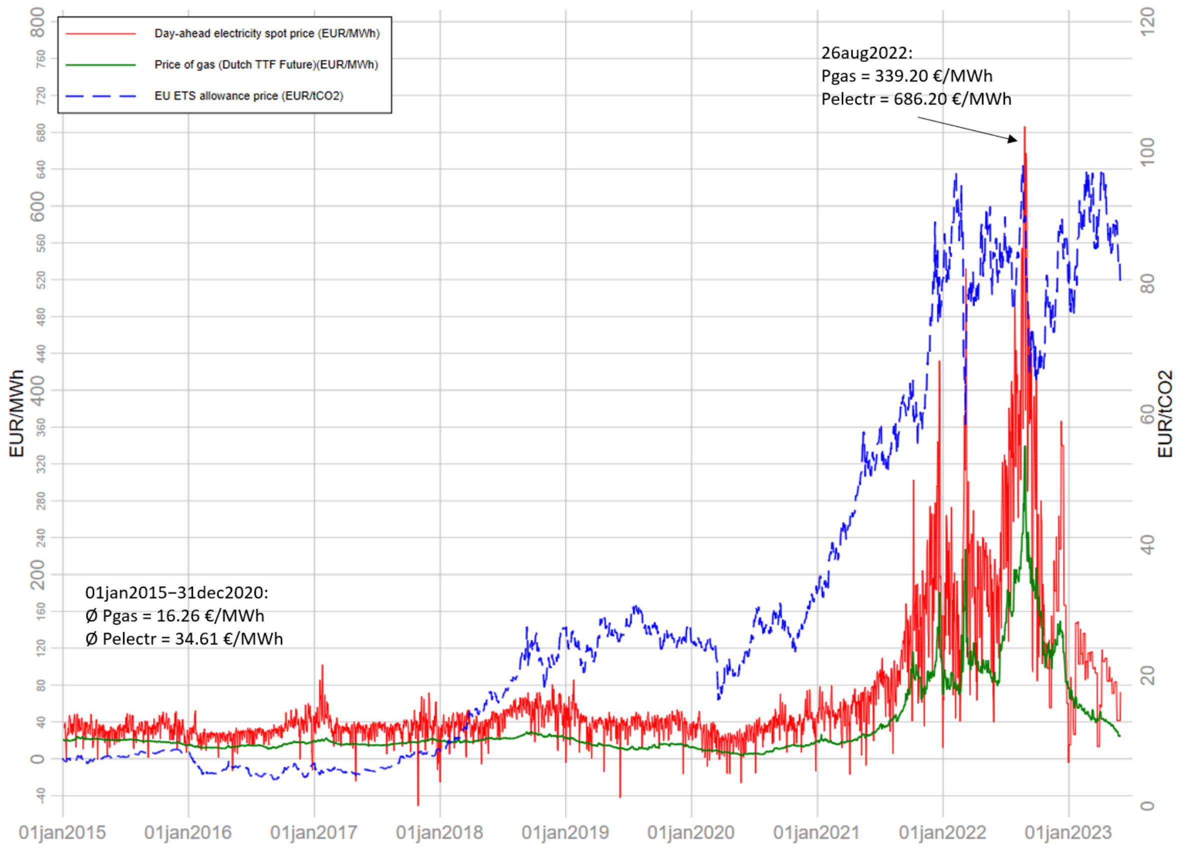


Figure 1: Commodity price developments, Germany

The graph shows the daily average German day-ahead spot price of electricity in €/MWh (P_{electr}), the daily closing values of the Dutch TTF one-month ahead future price of natural gas in €/MWh (P_{gas}), and the daily closing values of the EUA allowance price in €/tCO_2 (P_{CO2}). Period: January 1, 2015 – May 31, 2023. Correlations: Corr(P_{electr}, P_{gas}) = 0.93, Corr(P_{electr}, P_{CO2} = 0.75)

in the German electricity price in an ex-post econometric regression framework. The electricity price is modelled as a flexible, non-linear function of key influential factors, such as renewable energies, nuclear electricity, prices of natural gas and CO_2 allowances, electricity demand, trade, and unobserved fixed effects for hours of day, days of week, months of year, and years. The pronounced variation in the data, particularly from the energy crisis, allows modelling scenario developments for the coming years without having to rely on out-of-sample predictions.

Similarly, other studies (Fell and Kaffine, 2018; Holladay and LaRiviere, 2017) used the decline in the U.S. gas price due to the shale-gas boom (fracking) as an exogenous source of variation for econometric inference (on emissions). Moreover, while electricity price forecasts are often based on simulation or optimization models (Afman et al., 2017; Schmitt, 2022; Gierkink et al., 2022; Schäffer et al., 2019; Västermark et al., 2015; Zhuo et al., 2022), our econometric model exploits observed data (equilibrium observations) and is thus less reliant on market assumptions for a-priori modelling. To account for the endogeneity between the dependent variable, the electricity price, and an important control variable, electricity trade, we apply a two-stage least squares model and use the exogenous variation in wind electricity infeed in France as an instrumental variable.

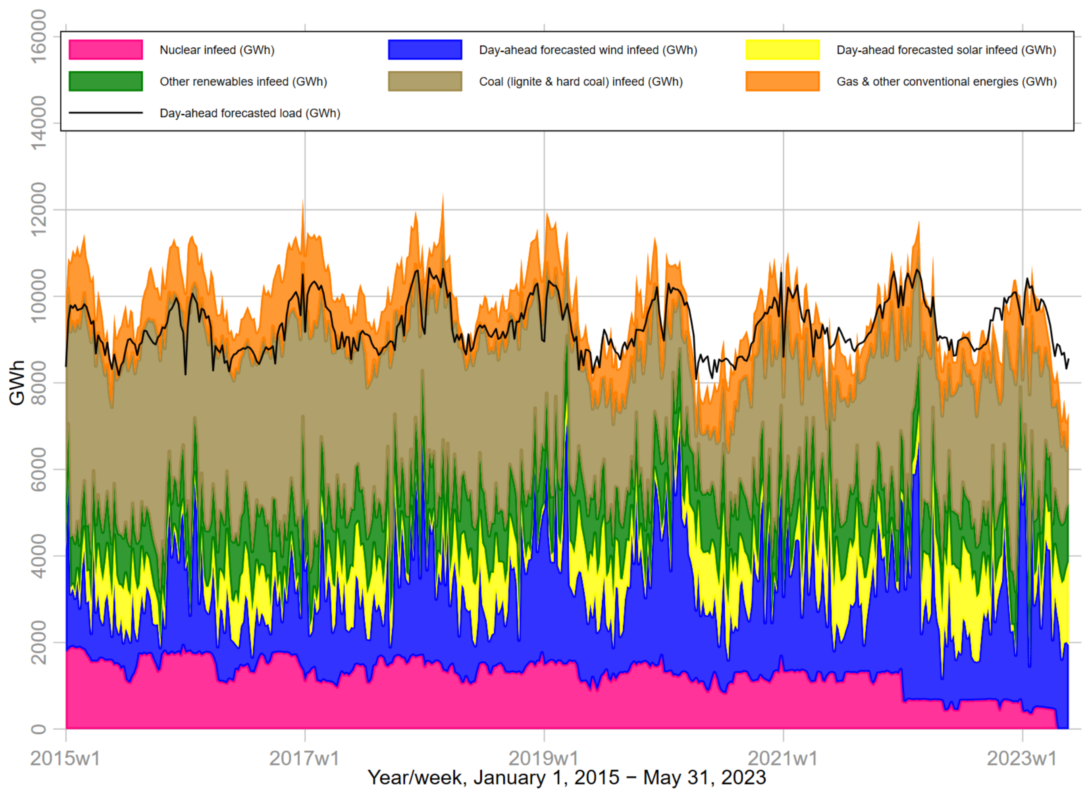


Figure 2: Load & stacked electricity infeed, Germany

The graph shows load (solid black line) and stacked infeed of nuclear, wind, solar, other renewables, coal, and gas plus other conventional power for the German electricity market. Period: January 1, 2015 – May 31, 2023, weekly averages. Supply overshooting load implies exports and imports otherwise.

The analysis yields a comprehensive set of findings. Firstly, this study evaluates the potential response of electricity prices to a ceteris-paribus change in one of its principal determinants, aiming to enhance comprehension of the influence of market trends. We find that the expansion of variable renewable energies creates downward pressure on the electricity price, whereas the other market trends, such as higher electricity demand due a further electrification of the economy, the nuclear phaseout, an increasing CO_2 allowance price, and a higher gas price surpassing pre-crisis levels, all result in an upward price pressure.

Secondly, we demonstrate how alterations in all key determinants simultaneously affect electricity prices based on our best-guess scenario predictions for the near future. Our findings suggest that the future electricity price is projected to be, on average, higher than pre-energy crisis levels. Moreover, our scenario analyses reveal that the electricity price level is highly responsive to changes, indicating that near-future electricity prices will exhibit significant volatility. This volatility stems from pronounced variations in CO_2 allowance prices, gas prices, and load, occurring on an hourly, daily, and seasonal basis. Notably, the volatile influx of renewable energy will play a substantial role in shaping electricity price volatility in the coming years.

An electricity price that is, on average, high yet fluctuating may convey important investment signals. For instance, it may incentivize investments in flexibility measures by presenting increased price arbitrage opportunities. Such investments could help mitigate the adverse ceteris-paribus impact of intermittent renewable expansions on their market values.

Our study is clearly related to the literature on the determinants of electricity prices (e.g., Ruibal and Mazumdar, 2008; Zarnikau et al., 2020), including studies of renewables' merit-order effect (e.g. Biber et al., 2022; Bushnell and Novan, 2021; Csereklyei et al., 2019; De Siano and Sapio, 2022; Maciejowska, 2020), market valuations of renewable energies (e.g., Liebensteiner and Naumann, 2022; Lòpez Prol et al., 2021), commodity price pass-through mechanisms (e.g., Fabra and Reguant, 2014; Hintermann, 2016, on a carbon price), and the impact of renewable subsidies on electricity prices (Abrell et al., 2019). While existing studies primarily concentrate on the impact of one or a few variables on an outcome variable, our study diverges by examining a comprehensive set of long-term fundamental drivers of electricity prices. We aim to elucidate how the evolution of these drivers may shape the future electricity price level until 2030.

Moreover, this study adds to the literature on flexibility-enabling investments in electricity markets. For example, Gonzales et al. (2023) demonstrate that network expansions can trigger investments in renewable energies. Fell et al. (2021) show that network investments can benefit renewable energies' environmental value (i.e. the reduction of environmental damages). Lazkano et al. (2017) find that research on energy storage can promote renewable energies. We touch upon these studies, showing that the major market trends in Germany may very well incentivize the integration of renewables and flexibility investments.

Despite the topic's political and economic relevance, to the best of our knowledge, there is only one recent study, which utilizes near-term data spanning the energy crisis and its recovery period, to assess the wholesale electricity price development of the near future. Gierkink et al. (2022; see also EWI, 2022, for an English summary) released a study in July 2022, in which Germany's electricity price, as predicted by an engineering model, is to range between 52–123 €/MWh by 2030 for different scenario variants, such as high or low gas prices, moderate or high growth in electricity demand, different renewable electricity expansion paths, and variations in the emissions allowance price. Moreover, Energy Brainpool (Schmitt, 2022), an energy market consultancy, modelled European electricity prices until 2050, also using an engineering model, with the forecast of a baseload price level of around 75 €/MWh by 2030, and with pronounced seasonal volatility. Although these studies are related and come to qualitatively similar results, they are not peer-reviewed and only cover the pre-crisis era. Thus, this study extends the body of knowledge by using a state-of-the-art econometric modelling framework, applied to near-time datasets, spanning the pre-crisis time, the entire energy-crisis, and the recovery phase.

The paper proceeds as follows. Section 2 identifies major market trends, which may influence the electricity price during the coming years. Section 3 introduces the empirical strategy, identification and modelling assumptions, and the data. Section 4 provides the results on ceteris-paribus impacts of key price determinants and scenario price predictions for the near future. Section 5 concludes.

2 Important market trends

We identify several important market trends, which we believe will be key drivers of the near-future electricity price development in Germany. We take 2030 as reference point, because this year is often used for predictions and forecasts in other studies. However, our main target is to make basic claims about the direction and approximate magnitude of how the electricity price will be shaped by major trends during the next years, but not to predict an exact price level by 2030. This is why we use conjectures about how our main variables of interest will develop until 2030.

Growth in electricity demand — The planned electrification of other economic sectors (sector coupling), foremost mobility and space heating, is thought to outweigh any efficiency gains by far. The idea of sector coupling is that economics sectors that currently rely heavily on fossil fuels will eventually be decarbonized by using sustainable green electricity as an essential input. Moreover, in the longer term, electrolysis for the production of hydrogen may also add to load. Gierkink et al. (2022), for example, predict a significant increase in Germany's demand for electricity until 2030 to 564 TWh (64,383 MWh per hour) in a scenario of a "moderate degree of electrification", which equates to an increase in load by 14% relative to 2022 according to our data. However, due to recently accelerated energy-efficiency improvements (Ruhnau et al., 2023; Sun et al., 2021), this prediction may overstate the load increase. In our view, a more realistic prediction is that load would gradually increase by 10% (to 61,936 MWh per hour) from 2022 until 2030.

Surge in intermittent renewable energies — Figure 2 shows that renewable energy infeed increased significantly between 2015 and May 2023 to a share of 46% in 2022. The German government set the goal to expand the share of renewable electricity to 80% by 2030 (Lepesant, 2023). While all renewable technologies are to increase their shares, the intermittent renewables in the form of wind and solar power are considered to be the backbone of the future energy system. However, for the time being, the actual renewable expansion lags significantly behind the plan, mainly due to long approval procedures for new renewable power stations and insufficient land designation (BMWK, 2012; Kyllmann, 2012). A realistic scenario may be that wind and solar electricity increase by 60% relative to 2022 (to about 45,000 MWh per hour). However, we acknowledge that this is a very crude forecast. Hence, even though it is yet unsure by how much wind and solar power will expand, it is likely that there will be a significant expansion of variable renewables during the coming years.

Increase in the carbon price — The EU ETS regulates the greenhouse-gas emissions of the power sector, energy-intensive heavy industry, and commercial aviation in all EU countries plus Iceland, Liechtenstein and Norway. While the average allowance price was only 6.4 €/tCO_2 during 2015–2017, it increased to 83 €/tCO_2 during 2022–May 2023 (see Figure 1), likely due to reforms of the EU ETS. In July 2021, ICIS, a commodity intelligence services firm, predicted an allowance price of €90 by 2030 (Simon, 2021). A 2022 market sentiment survey among 214 representatives of the International Emissions Trading Association (IETA, 2022) – a non-profit organization with the goal to establish a functional international emissions trading framework – yielded an expected EU ETS price of around €100. A near-term to net-zero-emissions approach was used to estimate the price of CO_2 in the U.S. of US$77–124 by 2030 (Kaufman et al., 2020). Also, the non-profit climate think tank Agora Energiewende (2023) assumes an allowance price of €100 in a recent study published in April 2023. To conclude, a tighter allowance cap reduction creates upward pressure on the allowance price, whereas the demand for allowances may also decrease due to decarbonization efforts. Moreover, economic shocks, which are difficult to foresee, may also affect the allowance price in any direction. While it is thus difficult to predict an accurate EU ETS allowance price, we consider a moderate path of the allowance price to around €100/CO_2 by 2030.

Price of natural gas higher than its pre-crisis level — Russia was Europe's main supplier of natural gas (Ruhnau et al., 2023). However, the war on Ukraine and Europe's aspiration to diversify away from its Russian energy dependency make it necessary to import natural gas from other regions. This can be achieved partly via pipelines through Europe's south, but mostly via more expensive imports of liquefied natural gas (LNG). After a tremendous gas price shock, with a peak of 339 €/MWh on 26 August 2022 (see Fig. 1), the market recovered significantly, to less than 24 €/MWh on 31 May 2023. Given that gas-fired power plants are still the price-setting marginal technology in Germany's electricity market during many hours of the year (the electricity day-ahead spot price and the natural gas price are correlated by 93%; see Fig 1), the gas price has been decisive of the electricity price development. Prognos (2022), for example, predicts that 35 €/MWh may be the long-term price ceiling for LNG from the U.S., 25 €/MWh would represent a moderate price scenario for a mix of pipeline gas and LNG, and 15 €/MWh as a lower-bound estimate, if Russia were to deliver most of the gas again. We thus assume that the the price of natural gas will be significantly higher than its pre-crisis level, in a range of 15–35 €/MWh.

Phaseout of nuclear power — In response to the Fukushima nuclear disaster on March 11, 2011, Germany turned off two nuclear power plants, and announced to shut down all 17 remaining nuclear reactors by December 2022 (Deutscher Bundestag, 2012). However, the energy crisis led to a revival of nuclear power in Europe – France (Chrisafis, 2022), the UK (Stevens, 2022), the Netherlands (Reuters, 2022), and Poland (Proctor, 2023) announced to invest heavily in new nuclear reactors until 2030 and beyond – and caused Germany to prolong the running time of its at that time three remaining nuclear power plants to April 15, 2023 (Fig. 2). Since April 15, 2023, Germany is phased out of nuclear power.

Lower net exports — Germany has been a net exporter of electricity. However, from 2015 until 2023, net exports declined significantly, from 65,000 MWh in 2015 to 30,000 MWh in 2022. This development is probably caused by the significant reduction in nuclear power during this time (Jarvis et al., 2022). As Germany phased out from its remaining nuclear reactors in April 2023, we expect net exports to fall further to about 2,000 MWh from then on.

Other developments — There may be other developments during the coming years, which may influence the electricity price, whereas of lesser importance than the major trends we defined above. For example, there are aspirations to increase the demand flexibility through flexible electricity contracts. However, this would require the roll-out of smart meters, which is unlikely to happen on a large scale in Germany (e.g., the law on "the restart of the digitalization of the energy transition" does not regulate a roll-out of smart meters on a national scale; Bundesregierung, 2023a). Moreover, the run-up of the hydrogen industry may significantly change the electricity market, providing a form of energy storage, whereas during the coming years, hydrogen may play a minor role (Wettengel, 2023). Also, economic shocks may influence the demand for electricity and thus the electricity price. Although we cannot rule out any major crises or upswings, our best-guess scenario is that energy demand will gradually increase over the coming years, mainly due to an expansion of electric vehicles and the electrification of space heating. Additionally, Germany scheduled its coal phaseout for 2038 (Bundesregierung, 2023b). This implies that no additional investments in lignite or hard coal generation capacity can be expected during the coming years. Yet a significant decline in coal-fired electricity generation is unlikely during the coming years.

3 Empirical strategy

3.1 Our approach and distinction from other prediction approaches

We use an ex-post econometric model applied to hourly historical data for the period Januar 1, 2015, through May 31, 2023, to infer about the impact of important trends, which may shape the electricity market of the future. The idea is that this econometric exercise allows for predictions of the electricity wholesale price with respect to changes in energy-market fundamentals, as triggered by these trends. The goal of the empirical modelling exercise is to give an outlook about the tendency of the electricity price over the coming years, not so much about its *exact* level or volatility. The value of this exercise is to allow for statements about the value of investments in flexibility-enabling measures, other electricity-generation technologies, and the deployment of electric vehicles.

In contrast to simulation models or other a-priori optimization models (e.g. fundamental market models using an optimization algorithm), our approach uses historic variation in the underlying variables to estimate their effects on the dependent variable. This makes our approach less dependent on market assumptions (as needed to calibrate a fundamental market model), whereas the data quality and variation play a key role. These conditions are met, having data from reliable sources (most data are derived from the ENTSO-E transparency platform) and sufficient variation (see figures 1 and 2; e.g. the price of gas varies strongly due to energy crisis and its latest recovery; the price of carbon permits rose significantly during 2018–2021). It is precisely the "abnormal" variation in market fundamentals caused by the energy crisis that make extrapolations into the future (such as a forecast for 2030) more reliable than using historical variation observed during "normal" times.

Moreover, machine-learning techniques, including random forest models, have gained traction in recent years for predicting the level and volatility of electricity prices (e.g., Tschora et al., 2022; Wang et al., 2022b). These approaches optimize a target value, often a statistical model's prediction error like the AIC or BIC, based on training data, often at the expense of neglecting economic theory. Such methodologies can enhance the predictive quality of available data without requiring an intricate understanding of the driving forces and complex economic channels, thereby informing trading strategies, for instance. However, the principal focus of this study is to comprehend the driving forces behind electricity prices and offer a rough price forecast to aid long-term investment decisions, rather than prioritizing precision in price prediction itself or minimizing computational time.

Another avenue for price predictions lies within typical time-series regression models (Shah et al., 2022; Wang et al., 2022a), such as vector autoregessive (VAR) models. Such models predict future values based on previously observed values and sometimes also partly on past observations of other integrated variables. While these models do not prioritize fundamental driving forces and economic channels, they rely on autocorrelation patterns such as trends, seasonality, or cycles to project future values.

The study conducted by Wang et al. (2022a) is particularly interesting, because it also investigates the German electricity spot price for the recent period spanning October 2018 through March 2022. It is noteworthy that the study identifies similar fundamental drivers as those applied in our research, including exogenous prices (gas, coal, and CO2 prices), internal variables (consumption and generation), and external variables (electricity trade between adjacent markets). However, there are notable distinctions between their approach and ours. Wang et al. (2022a) focus on a very near-term prediction horizon of only one month ahead, with a primary emphasis on minimizing prediction error. In contrast, our study extends to a long-term forecast horizon and primarily examines how changes in individual market fundamentals may influence future prices. Another significant point of differentiation lies in the treatment of potentially endogenous variables, such as electricity trade flows with neighboring countries, within the price regression. Although lags are used, this may not solve estimation bias (Bellemare et al., 2017), whereas our study addresses endogeneity through an instrumental-variables approach.

3.2 Econometric model

We estimate the electricity day-ahead spot price (P) as a function of renewable energies (R), nuclear electricity infeed (N), the EU ETS emission allowance price (P_{CO2}), the price of natural gas (P_{gas}), load (L), fixed effects (binary indicator variables) for each year (D_y), month of year (D_m), day of week (D_d), and hour of day (D_h), and a heteroscedasticity and first-order autocorrelation consistent stochastic error term (ϵ_t). A naive reduced-form model, which for now omits net exports as an important but potentially endogenous control variable, stands as follows:

$$\begin{aligned} P_t = &\beta_R R_t + \beta_{R^2} R_t^2 + \beta_N N_t + \beta_{N^2} N_t^2 + \beta_{P_{\mathrm{CO2}}} P_{CO2,t} + \beta_{P_{\mathrm{CO2}}{}^2} P_{CO2,t}^2 + \beta_{Pgas} P_{gas,t} + \\ &\beta_{Pgas^2} P_{gas,t}^2 + \beta_L L_t + \beta_{L^2} L_t^2 + D_y + D_m + D_d + D_h + \epsilon_t. \end{aligned} \tag{1}$$

The subscript t stands for each hour of the sample. The rich set of fixed effects ($\mathbf{D}$) controls for intra-day, daily, seasonal, and annual cycles. Equation 1 represents a flexible functional form in the spirit of a second-order Taylor approximation of the true but unknown functional form, where all regressors are introduced in levels and squared terms. This approach avoids imposing a linear functional relationship between the spot price and the right-hand-side variables, thus permitting potentially non-linear relationships. For instance, it is conceivable that increased renewable energy infeed might lead to a decrease in the spot price of electricity (i.e., $\hat{\beta}_R < 0$), albeit at a decreasing rate (i.e., $\hat{\beta}_{R^2} > 0$). Second-order Taylor expansions of unknown functional forms are popular in empirical estimations of production or cost functions (e.g., Gugler et al., 2017; Mydland et al., 2020), and have also found application in the context of energy markets (e.g., Liebensteiner and Naumann, 2022; Solarin and Bello, 2021).

From this model, it is possible to derive non-linear predictions of the electricity spot price for ceteris-paribus changes in the right-hand-side variables: $\partial P_t / \partial x_{i,t} = \hat{\beta}_i + 2 \cdot \hat{\beta}_{i^2} x_i$, with

$i \in \{R, N, P_{CO2}, P_{gas}, L\}$. For instance, the predicted electricity spot price in response to a change in variable renewable energies is: $\partial P_t/\partial R_t = \hat{\beta}_R + 2\hat{\beta}_{R^2}R$, where the hats indicate parameter estimates. The predicted values can then be evaluated for any level of infeed of variable renewable energies. The outcomes of this analysis are depicted in Figure 3. Furthermore, computing the total derivative, $\partial P_t = \sum_i \partial P_t/\partial x_{i,t} = \sum_i(\hat{\beta}_i + 2 \cdot \hat{\beta}_{i^2}x_i)$ provides the change in the predicted price for a simultaneous change in all fundamental variables. Incorporating the scenario predictions yields the outcomes illustrated in Figure 4.

Electricity trade (net exports, EX) represents a significant variable to consider, yet it demonstrates a potentially endogenous relationship with the dependent variable. Specifically, electricity flows from the higher-price market to the lower-price market until the prices equate or interconnection capacity is exhausted (Gugler et al., 2018). Consequently, trade is contingent upon electricity prices (both in the home and sending markets) and also influences electricity prices (in both markets), contributing to an endogeneity challenge.

This is why we estimate a two-stage least squares (2SLS) model, where we instrument for EX to obtain consistent and unbiased estimates. As an exogenous source of variation, we use wind electricity infeed in France (WFR), which, by definition, can only impact Germany's electricity price through trade. Moreover, on average, Germany imports most of its electricity from France. The first-stage regression equation is:

$$\begin{aligned} EX_t =& \beta^{1st}_{WFR} WFR_t + \beta^{1st}_R R_t + \beta^{1st}_{R^2} R_t^2 + \beta^{1st}_N N_t + \beta^{1st}_{N^2} N_t^2 + \beta^{1st}_{P_{\text{CO2}}} P_{CO2,t} + \beta^{1st}_{P_{\text{CO2}}{}^2} P^2_{CO2,t} + \\ & \beta^{1st}_{Pgas} P_{gas,t} + \beta^{1st}_{Pgas^2} P^2_{gas,t} + \beta^{1st}_L L_t + \beta^{1st}_{L^2} L_t^2 + D_y + D_m + D_d + D_h + \epsilon^{1st}_t. \end{aligned} \quad (2)$$

The second-stage regression equation is:

$$\begin{aligned} P_t =& \beta_{EX} \widehat{EX}_t + \beta_R R_t + \beta_{R^2} R_t^2 + \beta_N N_t + \beta_{N^2} N_t^2 + \beta_{P_{\text{CO2}}} P_{CO2,t} + \beta_{P_{\text{CO2}}{}^2} P^2_{CO2,t} + \\ & \beta_{Pgas} P_{gas,t} + \beta_{Pgas^2} P^2_{gas,t} + \beta_L L_t + \beta_{L^2} L_t^2 + D_y + D_m + D_d + D_h + \epsilon_t, \end{aligned} \quad (3)$$

where $\widehat{EX}_t$ is the prediction from the first-stage regression.

3.3 Identification and modelling assumptions

IV assumptions — This model should produce unbiased estimates if the exclusion restriction is satisfied and the assumption of instrument relevance holds. *Instrument relevance* necessitates that the instrumental variable (WFR) exhibits sufficient correlation with the endogenous variable (EX), which can be tested. Indeed, the first-stage regression demonstrates a statistically significant partial correlation and yields a high effective first-stage F statistic (Olea and Pflueger, 2013), rejecting the null hypothesis of instrument weakness (see Appendix Table A1).

The *exclusion restriction* demands that the instrument affects the outcome variable (P) solely through the endogenous variable (EX). Although this assumption cannot be directly tested, it must be justified by economic reasoning. By definition, wind energy in France can only influence the German electricity price through trade, supporting this notion. More electricity supply from wind power in France thus alleviates the need for imports from Germany (Germany is a net exporter to France, as shown in the sample statistics provided in Table 1).

If wind infeed in France and Germany significantly overlap, this could challenge the validity of the exclusion restriction. However, in our dataset, the correlation between these two variables is only 0.53, suggesting that there is ample exogenous variation in wind infeed in France that influences trade between the two countries.

Assumption of no structural breaks — Our model utilizes historical variations in the fundamental drivers of the electricity spot price to forecast future price levels. In doing so, we assume that no major structural changes will occur during our forecast horizon until 2030. For instance, the European Commission's recently announced plans for a comprehensive reform of wholesale electricity markets, involving the introduction of Power Purchase Agreements (PPAs) and two-sided contracts for differences for new renewable capacity, may impact the subsidy mechanisms for renewable energies. However, we consider these changes as adjustments rather than structural breaks in the market dynamics. While these changes may affect renewable deployment, they are not considered to constitute structural breaks in the market dynamics.

Moreover, an increased use of electricity storage could fundamentally transform the market. Yet, as of now, there are no indications of significant investments in storage capacity in Germany or Europe until 2030.

Additionally, changes in market power could pose a threat to the assumption of no structural breaks. Nevertheless, our sample encompasses periods of "normal" commodity prices for gas and coal, during which market power was likely constrained, as well as the crisis period, which was characterized by excessive market power. Consequently, we are confident that our model captures a substantial degree of variation in market power. Even in future situations dominated by renewables, firms may not bid at their marginal cost due to market power (Fabra and Llobet, 2023). Therefore, we anticipate that market power in the future is unlikely to deviate significantly from the range of market power embodied in our dataset.

Exogeneity of regressors — Furthermore, the identification of the effects of interest – how the right-hand-side variables influence the electricity spot price – relies on an exogeneity assumption. This assumption posits that variable renewables infeed, nuclear power infeed, the emission allowance price, the natural gas price, and load are exogenously determined. In other words, the right-hand-side variables are presumed to be determinants of the electricity price, while variations in the electricity price do not cause changes in any of the right-hand-side variables (which could potentially introduce an endogeneity bias in our estimations). It is noteworthy in this context that despite a lengthy sample horizon (January 1, 2015, to May 31, 2023), the regression (equation 2) constitutes a *short-term model* of hourly price setting.

Regarding renewable energy infeed, wind and solar electricity generation are driven by meteorological conditions, such as wind speeds and solar radiation. Consequently, in the short run, their effects can be considered exogenous. Run-of-river hydropower serves as baseload and generates electricity whenever feasible. Furthermore, these energy sources have near-zero marginal costs, allowing them to contribute to the grid before other technologies with positive marginal costs. Biomass and biogas also have positive marginal costs but benefit from prioritized infeed, enabling them to integrate into the system ahead of other technologies. Nuclear electricity also serves as baseload, operating at full capacity whenever available at low marginal costs. Therefore, nuclear electricity can be treated as exogenous.

Table 1: Sample statistics & data sources

Variables	Source	Mean	S.D.	Pctl 5	Pctl 50	Pctl 95
P	ENTSO-E	69.58	87.69	11.56	39.97	250.66
R	ENTSO-E	24,776	10,994	10,255	22,913	45,435
N	ENTSO-E	7,413	2,344	2,847	7,815	10,552
L	ENTSO-E	55,218	9,378	40,359	55,182	69,523
EX	ENTSO-E	4,513	5,090	-4,663	5,068	12,000
WFR	ENTSO-E	3,420	2,683	750	2,535	9,246
PCO2	investing.com	30.74	28.15	4.93	23.52	87.98
Pgas	investing.com	35.17	43.31	8.29	18.73	128.51

Notes: Sample period: 01jan2015–31may2023. 73,432 hourly observations.
P … Day-ahead electricity spot price (€/MWh), hourly resolution
R … Renewable energy infeed (MWh), hourly resolution
N … Nuclear energy infeed (MWh), hourly resolution
L … Load, day-ahead forecast (MWh), hourly resolution
EX … Net exports (MWh), hourly resolution
WFR … Wind energy infeed in France, d.a. forec. (MWh), hourly resolution
P_{CO2} *… Emission allowance price (EUA) (€/t*CO_2*), daily resolution*
P_{gas} *… Price of natural gas (€/MWh), daily resolution*

The emissions allowance price is determined by the demand for and supply of emission allowances within the scope of the EU ETS. It is unlikely, especially in the short term, that changes in electricity prices significantly impact the EUA price level (Liebensteiner and Naumann, 2022). The price of natural gas is established at the international level based on supply and demand dynamics. Consequently, the European gas price is unlikely to be influenced by short-term changes in the electricity spot price.

Moreover, although electricity demand may respond to wholesale electricity prices in the long run, it is reasonable to assume that short-term fluctuations in wholesale electricity prices do not significantly affect demand. Final consumers of electricity typically maintain long-term retail contracts (usually for a year; Gugler et al., 2023), insulating them from short-term price fluctuations. In the short run, electricity demand is primarily determined by meteorological conditions, seasonality, and economic activity.

Similar modeling assumptions have been employed in econometric studies on electricity prices, including those investigating the merit-order or cannibalization effect of renewable energies (Bushnell and Novan, 2021; Clo et al., 2015; Csereklyei et al., 2019; Liebensteiner and Naumann, 2022; Lòpez Prol et al., 2021; Maciejowska, 2020; Welisch et al., 2016).

The model does not include variables on the electricity supply by coal- or gas-fired power plants because it would be endogenous to the electricity price, which could introduce estimation bias. While gas supply is implicitly modelled through variations in the gas price, which is highly correlated with the coal price, and variations in load (which determines the operation of plants), the model basically assumes coal supply to keep its somewhat decreasing trend. This assumption seems reasonable until 2030, considering Germany's plan for coal phaseout, which is scheduled for 2038 (Bundesregierung, 2023b) – well beyond our modeling horizon.

3.4 Data

Hourly data on day-ahead electricity spot prices, day-ahead forecasts of load and wind and solar power, and electricity infeed by technology class are obtained from the ENTSO-E (2023) transparency platform. The daily closing value of EU emission allowances (EUA) is obtained from the financial market platform investing.com (2023a). As the price of natural gas, the daily closing price of the Dutch TTF one-month ahead future price from the Intercontinental Exchange (ICE), provided by investing.com (2023b), is used. The sample period spans 01jan2015–31may2023.

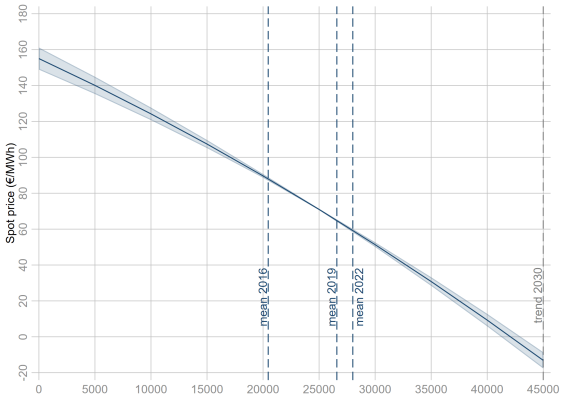
Table 1 presents sample statistics and descriptions of all variables employed in the analysis. Evidently, all variables exhibit substantial variation, which can be leveraged for econometric inference.

4 Results

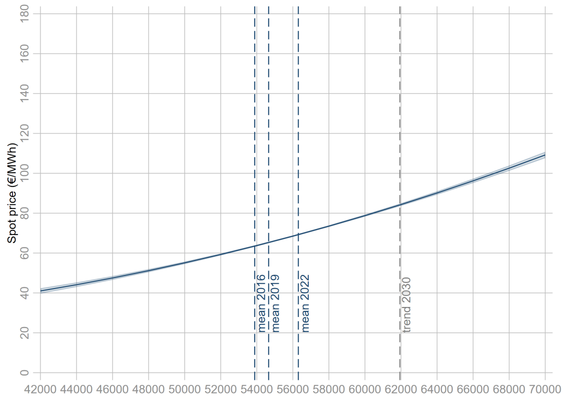
4.1 Ceteris-paribus impacts of key price determinants

The estimates of the econometric model allow to assess how strongly the electricity price reacts to each identified market trend, while other influential factors are held constant at their sample means. The first- and second-stage regression estimates are presented in Appendix tables A2 and A1, respectively. Using the second-stage estimates, we derive average marginal effects (as described in Section 3.2) and elasticities (i.e. the percentage change in the electricity price for a one-percent change in the variable of interest), as provided in Table 2. The strongest electricity price reactions are obtained for changes in load (1.89%) and renewables (-1.36%), whereas the elasticities of the other variables of interest lie in between those values. Figure 3 visualizes the main estimates as ceteris-paribus changes in the predicted electricity price with respect to the key variables of interest.

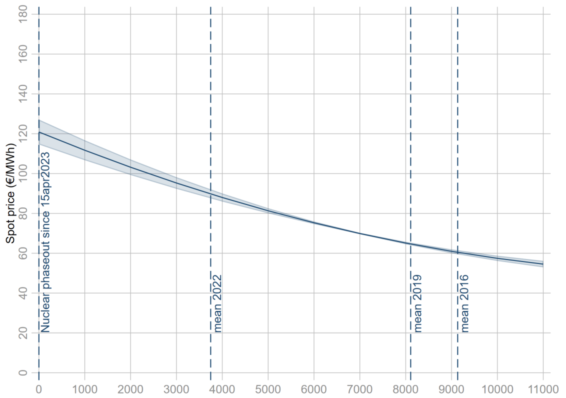
Figure 3a shows that renewable energy infeed has a price-depressing effect on the electricity spot price (the merit-order effect), which intensifies with higher renewable energy penetration levels. A surge in renewable electricity during the coming years will thus significantly deter the electricity price. Figure 3b indicates a price-increasing effect of load. A growth in load through a further electrification of the economy will therefore create an upward price pressure. Figure 3c displays the price-decreasing effect of nuclear energy. Thus, a nuclear phaseout elevates the electricity price. The convexity of the curve implies that the phaseout of the last three nuclear reactors on April 15, 2023 led to a significant ceteris-paribus upward price pressure. Figure 3d reveals an increasing impact of the CO_2 allowance price on the predicted electricity price. An increasing allowance price in the coming years will accordingly push the electricity price upwards. Figure 3e shows a strong positive and almost linear impact of the gas price on the electricity price. During the energy crisis in 2022, the gas price skyrocketed, which caused a significant ceteris-paribus electricity-price push. However, during the coming years, the gas price is assumed to recover but stay well above its pre-crisis level, which creates upward pressure on the electricity price relative to pre-crisis times. Finally, Figure 3f shows a positive impact of exports on the electricity price, which is in line with the economic theory of trade. That is,



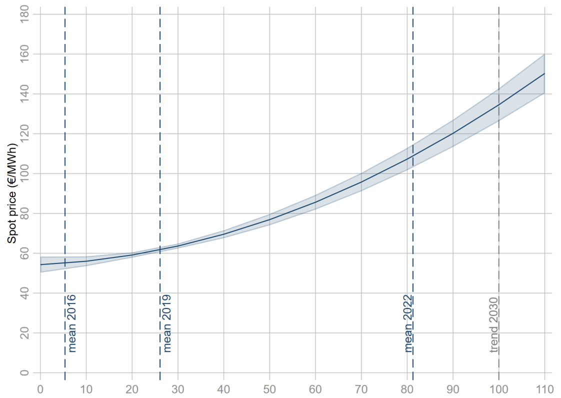
(a) Renewable energy infeed (MWh per hour)



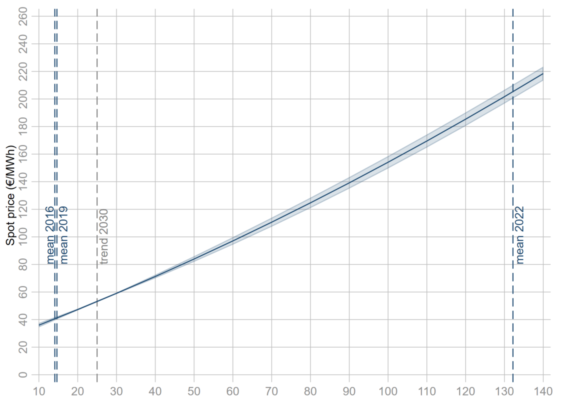
(b) Load (MWh per hour)



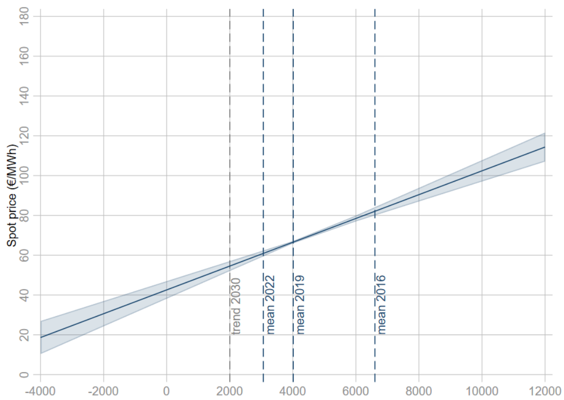
(c) Nuclear energy infeed (MWh per hour)



(d) EU ETS allowance price (€/tCO_2)



(e) Price of gas (€/MWh)



(f) Net Exports (MWh per hour)

Figure 3: Ceteris-paribus changes in the predicted electricity spot price

The graph shows predicted values of the electricity spot price for ceteris-paribus changes in fundamental variables, while other variables are held constant at their sample means. Sample size: 73,432 observations. 95% confidence intervals are provided based on heteroscedasticity and autocorrelation consistent standard errors.

Table 2: Average marginal effects and elasticities

Variable	Sample mean	Avg. marginal effect	Elasticity (relative effect of a 1% increase from the sample mean)
R	24775.93	-0.00382	-1.36%
N	7412.50	-0.00483	-0.51%
P_{CO2}	30.74	0.53242	0.24%
EX	4502.49	0.00598	0.39%
P_{gas}	35.17	1.22236	0.62%
L	55217.52	0.00238	1.89%

All marginal effects are statistically significant at the 1% level. Sample mean electricity price is €69.58.
R ... Renewable energy infeed (MWh)
N ... Nuclear energy infeed (MWh)
P_{CO2} ... Emission allowance price (EUA) (€/tCO_2)
EX ... Net Exports (MWh)
P_{gas} ... Price of natural gas (€/MWh)
L ... Load, day-ahead forecast (MWh)

exports can be understood as additional demand from abroad, which increases the price, while imports can be understood as additional supply, which reduces the price (see Gugler et al., 2018). Germany is a net exporter of electricity, whereas net exports have decreased over time, resulting in a downward price pressure. During the coming years, we expect net exports to further decline to about 2,000 MWh, because of the completed nuclear phaseout by 15 April 2023.

In sum, each of the identified trends has a significant ceteris-paribus impact on the electricity price. A surge in renewable energy will create serious downward pressure on the electricity price. Moreover, less net exports also contribute to a downward price pressure. By contrast, all other market trends (growth in load, nuclear phaseout, high carbon price, higher gas price than before the crisis) work in the opposite direction.

4.2 Scenario predictions for the near future

We use our econometric model to predict the electricity price in the near future for varying scenarios, based on the identified market trends. The price prediction should not be taken literally, but be understood as an indication about the price development and its sensitivity to changing market circumstances, relative to historically observed prices.

Baseline scenario — As a baseline scenario, we assume that the market trends develop gradually to what we assume as their potential 2030 values. That is, we assume a gradual (linear) expansion of variable renewables by 60% (from 28,000 MWh in 2022 to 45,000 MWh in 2030). Load is assumed to grow by 10% (to 62,000 MWh in 2030) relative to 2022 (56,300 MWh). The carbon price is set to grow from 81 €/tCO_2 in 2022 to 100 €/tCO_2 in 2030. Nuclear electricity is already phased out and thus assumed to stay a zero MWh. We assume a gas price of 25 €/MWh, corresponding to the "moderate" gas price scenario of Prognos (2022) (as discussed

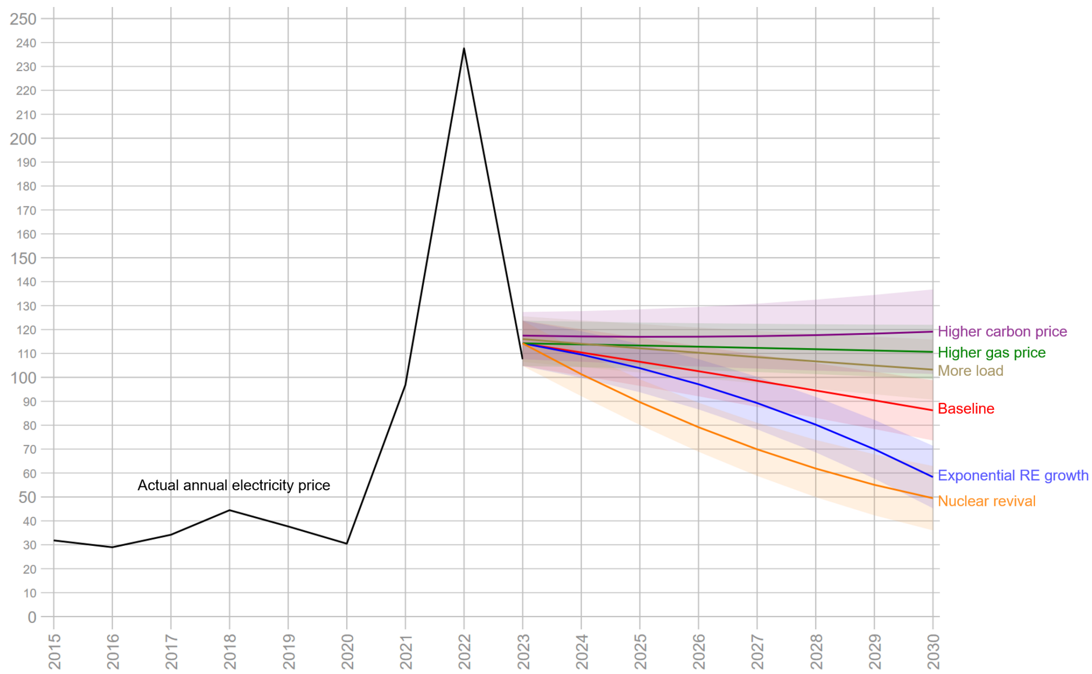


Figure 4: Electricity price projections for different scenarios

The graph shows the predicted electricity wholesale price for different scenarios and the 95% confidence intervals.

in Section 2). Net Exports are assumed to be 2,000 MWh. Figure 4 shows that the baseline scenario yields an electricity price in the near future, which is significantly higher than during the pre-crisis period. For example, by 2025, the price projection is 104 €/MWh (confidence interval: 94–114 €/MWh), which is about 6.5 times higher than during the pre-crisis period (16 €/MWh, see Figure 1).

Price-increasing scenarios — It may well be that price-increasing trends could be more pronounced that assumed in the baseline scenario. Hence, a scenario variant "*higher gas price*" assumes the price of natural gas to gradually increase from 25 €/MWh in 2023 to a relatively high level of 45 €/MWh in 2030. Such a scenario is possible if LNG imports from the U.S. determined the costs of gas in Germany, and/or if the gas price increased over time. Again, all other baseline assumptions apply. For scenario, Figure 4 shows a significantly higher price prediction until 2030, while during 2023–2025, the deviation from the baseline scenario if negligible (and statistically insignificant, as the confidence intervals overlap). Similarly, a scenario of a "*higher carbon price*" assumes a stronger increase in the carbon price to 120 €/tCO_2 by 2030, which yields again a higher price prediction than the baseline scenario. Another scenario "*more load*" assumes load to increase stronger, to +20% by 2030 relative to 2022. This could be if the electrification of the economy happens faster than anticipated. This scenario also shows a higher price projection than the baseline scenario, but with largely overlapping confidence intervals.

Price-decreasing scenarios — It could be that the initial barriers to a significant renewables expansion (e.g., a shortage of skilled labor to install the renewable power stations, time-consuming bureaucracy for licensing procedures and environmental impact assessments, and

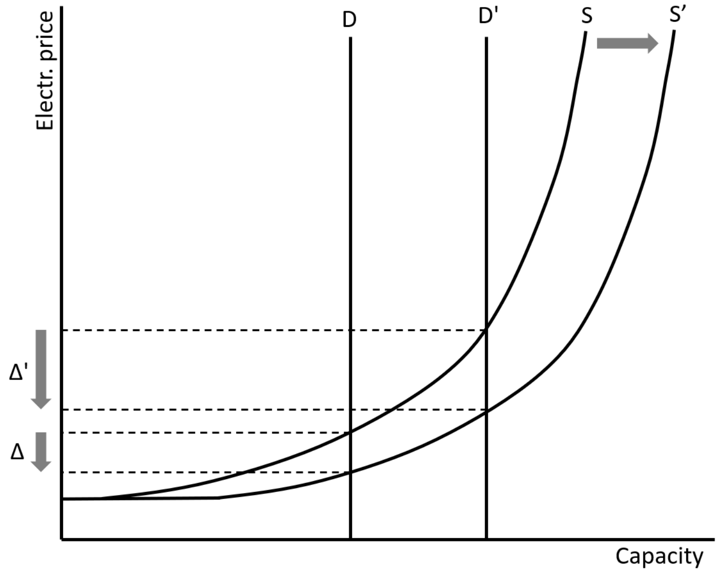


Figure 5: Price effects of a change in baseload when demand intersects supply in the steep or flat part

The graph schematically demonstrates that an increase in baseload (e.g. a reduction in nuclear power) from S to S' has a more pronounced price-reducing effect ($\Delta' > \Delta$) when demand intersects supply in the steep part (D') compared to when demand meets supply in the flat part (D).

location problems) are alleviated over time. Hence, in an alternative scenario variant "*exponential RE growth*", we assume an exponential growth of intermittent renewables to 51,000 MWh (i.e. +82%). All other baseline assumptions apply. In this scenario, Figure 4 shows a lower electricity price in the longer run, whereas during 2023–2025, there is hardly a difference to the baseline projection (the confidence intervals overlap). Finally, a scenario of a "*nuclear revival*" assumes that Germany gradually reverts back to Nuclear power. By 2030, nuclear infeed reaches its level of 2015 (10,000 MWh). We also gradually adjust net exports back to their 2015 values until 2030 (from 2,000 MWh in 2023 to 6,462 MWh in 2030). This scenario yields the lowest projected price trajectory. An explanation of why nuclear power has such a strong impact on the electricity price is provided in Figure 5. It shows that an increase in baseload electricity has a stronger price-reducing effect when the electricity price is initially high (i.e. when demand intersects supply in the steep part) compared to an initially lower price level. Yet, even in this case, the electricity price remains at a higher level during the coming years than during the pre-crisis period.

Of course, other scenario variants are also possible, including such where multiple variables change together. In any case, our scenario variants provide evidence that the near-future electricity price may be significantly higher than its long-run pre-crisis average.

Moreover, the the electricity price of the future may exhibit a more pronounced variation. Missing baseload electricity from nuclear power stations, but significantly more infeed from intermittent renewables, paired with, on average, high carbon and gas prices and a growth in load increase the likelihood of a pronounced price volatility. This is because renewable energy infeed, load, the price of gas, and the carbon price exhibit substantial variation within a day, from day to day, and across seasons (see figures 1 & 2). Indeed, the different scenario variants already show that the predicted electricity price can vary substantially for variations in renewables, carbon and gas prices, and load. Hence, any intra-day, day-to-day, or seasonal volatility in these variables will affect the electricity price volatility, especially when the price level is high on average.

4.3 Robustness: predictions from a fundamental market model

To verify the consistency of the econometric model's price prediction, we also applied an a-priori fundamental energy system model to the baseline scenario values. *MyPyPSA-Ger* is an open-source expansion model, which optimizes generation and grid capacities in Germany's electricity sector (Abuzayed and Hartmann, 2022). The model features highly detailed spatial dimensions with up to 317 nodes in the electrical network and a temporal resolution of up to 8760 hours per year. The model considers multiple factors, including future electricity demand, fuel prices, technology investment costs and performance, CO_2 allowance price, and governmental policies and regulations. The model minimizes the annualized system costs via LP optimization and adopts a myopic (yearly) perspective, while adhering to a country-wide CO_2 cap. All modelling details are provided in Abuzayed and Hartmann (2022).

The fundamental model's price prediction is visualized in Appendix Figure A1, together with the econometric baseline prediction. In line with our main econometric result, the fundamental model yields a price prediction which is significantly higher than during pre-cisis times. Moreover, the fundamental model's predicted price trajectory falls largely within the baseline scenario's 95% confidence interval, confirming our main econometric result.

5 Conclusions and Policy Implications

We identify several market trends that may shape the German electricity price over the next few years. An expansion of renewable energy, most of all via intermittent wind and solar power, will create downward pressure on the electricity price. Lower net exports also reduce the electricity price. On the contrary, an increase in load, a decline in baseload electricity supply through the nuclear phaseout, a climbing CO_2 emissions allowance price, and a higher gas price than before the crisis tend to elevate the electricity price. Using an econometric model applied to high-frequency near-time data spanning January 2015 through May 2023, it is shown that the individual driving forces have pronounced ceteris-paribus effects on the electricity price. The model is estimated in a two-stage regression framework, because we instrument for the potentially endogenous relationship between an important control variable, electricity trade, and the dependent variable, price.

Moreover, we use the model's estimates to predict the electricity price during the coming years. We establish a baseline scenario, based on assumptions of how the main price determinants may evolve over time, as identified by our major market trends. This analysis indicates that the electricity price will be significantly higher during the coming years than its long-run pre-crisis mean. An a-priori fundamental market model confirms this result. Several scenario variants adjust the baseline assumptions. These variations show that the price projections can differ significantly, depending on how the price determinants develop over time, whereas the main finding that the electricity price will be higher than during the pre-crises era is confirmed. From these scenario variations, we can also deduct that the high intra-day, day-today, and seasonal variability of the main driving forces of the electricity price (i.e. weather-dependent renewables, the gas price, the carbon allowance price, and load) may significantly increase the volatility of the near-future electricity price. Hence, even small variations in one of our price-predicting trends can have material impact on the electricity price of the near future.

These results have important policy implications, because expectations about the electricity price send investment incentives, bears distributional consequences, and shape market-design debates. A high electricity price level and volatility will increase the value of flexibility in the market (Kern et al., 2023; Mays, 2021). Flexibility investments are much needed to ensure demand-supply parity in a system that has pronounced intermittent infeed by a high share of wind and solar power. For example, energy-efficiency improvements are more lucrative for a high electricity price. It also promotes the central target of the EU Commission (European Commission, 2023) to empower and incentivize consumers to react to price signals and to adapt their demand (demand response), such as by shifting load from peak to off-peak times and to make use of increased arbitrage opportunities. Similarly, storage operators profit from higher price spreads, pushing investments in storage capacity (Liebensteiner et al., 2023). Moreover, a high price benefits low-marginal-cost supply technologies, especially renewables. If renewables become economical for a higher electricity price, support payments for green energies may be reduced, which would increase the public support for the decarbonization transition.

A high electricity price may also influence the current discussion about a reform of the EU electricity market design. With the phase-out of fossil-fueled power plants and insufficient new investments in capacity generation, a lack of non-weather dependent and steerable generation capacity is most likely. Expectations of high electricity prices can counteract this by sending the necessary price signals of scarce supply. Plus, it mitigates the need for additional capacity remuneration mechanisms, such as capacity markets, which are prone to cause distorting effects on the wholesale market (Bublitz et al., 2019). A market design reform may also be less pressing, because renewable energies' cannibalization of their own market values (Liebensteiner and Naumann, 2022; Lòpez Prol et al., 2021) is no longer an issue. Yet, it may put pressure on politicians to protect consumers and industry from increasing electricity cost. This could lead to a re-enactment of the temporarily introduced revenue cap for electricity generation of 180 €/MWh (European Council, 2023) in late 2022: Expiring end of June 2023, it was initially introduced due to surging gas prices, but may present a tool to prevent future energy poverty (Guan et al., 2023), especially for vulnerable households, but also for industrial and commercial consumers facing severe production cost increases. Hence, this study's findings may aid evidence-based policy making.

References

Abrell, J., Kosch, M., Rausch, S., 2019. Carbon abatement with renewables: Evaluating wind and solar subsidies in Germany and Spain. Journal of Public Economics 169, 172–202.

Abuzayed, A., Hartmann, N., 2022. MyPyPSA-Ger: Introducing CO2 taxes on a multi-regional myopic roadmap of the German electricity system towards achieving the 1.5° C target by 2050. Applied Energy 310, 118576.

Afman, M., Hers, S., Scholten, T., 2017. Energy and electricity price scenarios 2020–2023–2030. CE Delft, January.

Agora Energiewende, 2023. Klimaneutrales Stromsystem 2035: Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann. April 2023 https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_11_DE_KNStrom2035/A-EW_264_KNStrom2035_WEB.pdf.

Baratsas, S.G., Niziolek, A.M., Onel, O., Matthews, L.R., Floudas, C.A., Hallermann, D.R., Sorescu, S.M., Pistikopoulos, E.N., 2021. A framework to predict the price of energy for the end-users with applications to monetary and energy policies. Nature Communications 12, 18.

Bellemare, M.F., Masaki, T., Pepinsky, T.B., 2017. Lagged explanatory variables and the estimation of causal effect. The Journal of Politics 79, 949–963.

Biber, A., Tunçinan, M., Wieland, C., Spliethoff, H., 2022. Negative price spiral caused by renewables? electricity price prediction on the German market for 2030. The Electricity Journal 35, 107188.

BMWK, 2012. Bericht des Bund-Länder-Kooperationsausschusses zum Stand des Ausbaus der erneuerbaren Energien sowie zu Flächen, Planungen und Genehmigungen für die Windenergienutzung an Land. German Federal Ministry for Economics and Climate Action, 26 Oct, www.bmwk.de/Redaktion/DE/Downloads/E/EEG-Kooperationsausschuss/2022/bericht-bund-laender-kooperationsausschuss-2022.pdf?__blob=publicationFile&v=10.

Bublitz, A., Keles, D., Zimmermann, F., Fraunholz, C., Fichtner, W., 2019. A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms. Energy Economics 80, 1059–1078.

Bundesregierung, 2022. We're tripling the speed of the expansion of renewable energies. The German Government, December 22, www.bundesregierung.de/breg-de/themen/klimaschutz/amendment-of-the-renewables-act-2060448, accessed on June 6, 2023.

Bundesregierung, 2023a. Gesetz zum Neustart der Digitalisierung der Energiewende. German Federal Guvernment. Bundesgesetzblatt, Teil I, Nr. 133, 26 May 2023. www.recht.bund.de/bgbl/1/2023/133/VO.html.

Bundesregierung, 2023b. Von der Kohle zur Zukunft. The German Government, February 24, www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/kohleausstieg-1664496, accessed on June 21, 2023.

Bushnell, J., Novan, K., 2021. Setting with the sun: The impacts of renewable energy on conventional generation. Journal of the Association of Environmental and Resource Economists 8, 759–796.

Chrisafis, A., 2022. France to build up to 14 new nuclear reactors by 2050, says Macron. The Guardian, February 10, www.theguardian.com/world/2022/feb/10/france-to-build-up-to-14-new-nuclear-reactors-by-2050-says-macron.

Clo, S., Cataldi, A., Zoppoli, P., 2015. The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. Energy Policy 77, 79 – 88.

Csereklyei, Z., Qu, S., Ancev, T., 2019. The effect of wind and solar power generation on wholesale electricity prices in Australia. Energy Policy 131, 358–369.

De Siano, R., Sapio, A., 2022. Spatial merit order effects of renewables in the Italian power exchange. Energy Economics 108, 105827.

De Vos, K., 2015. Negative wholesale electricity prices in the German, French and Belgian day-ahead, intra-day and real-time markets. The Electricity Journal 28, 36 – 50.

Deutscher Bundestag, 2012. Der Einstieg zum Ausstieg aus der Atomenergie. www.bundestag.de/webarchiv/textarchiv/2012/38640342_kw16_kalender_atomaustieg-208324.

ENTSO-E, 2023. Transparency platform. transparency.entsoe.eu/, accessed on June 1, 2023.

European Commission, 2023. Clean energy for all Europeans package. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en, accessed on June 28, 2023.

European Council, 2023. Council formally adopts emergency measures to reduce energy prices. October 6, www.consilium.europa.eu/en/press/press-releases/2022/10/06/council-formally-adopts-emergency-measures-to-reduce-energy-prices/.

EWI, 2022. Energy prices in Europe to remain at a high level in the medium term. Institute of Energy Economics at the University of Cologne (EWI), July 14, www.ewi.uni-koeln.de/en/news/esys/.

Fabra, N., Llobet, G., 2023. Auctions with privately known capacities: Understanding competition among renewables. The Economic Journal 133, 1106–1146.

Fabra, N., Reguant, M., 2014. Pass-through of emissions costs in electricity markets. American Economic Review 104, 2872–2899.

Fell, H., Kaffine, D.T., 2018. The fall of coal: Joint impacts of fuel prices and renewables on generation and emissions. American Economic Journal: Economic Policy 10, 90–116.

Fell, H., Kaffine, D.T., Novan, K., 2021. Emissions, transmission, and the environmental value of renewable energy. American Economic Journal: Economic Policy 13, 241–272.

Frew, B., Anwar, M.B., Dalvi, S., Brooks, A., 2023. The interaction of wholesale electricity market structures under futures with decarbonization policy goals: A complexity conundrum. Applied Energy 339, 120952.

Gierkink, M., Çam, E., Diers, H., Keutz, J., Kopp, J., Lilienkamp, A., Moritz, M., Wiedmann, M., Zinke, J., 2022. Szenarien für die Preisentwicklung von Energieträgern. Energiewirtschaftliches Institut (EWI) an der Universität zu Köln. Studie Im Auftrag des Akademienprojekts Energiesysteme der Zukunft" (ESYS).

Gonzales, L.E., Ito, K., Reguant, M., 2023. The investment effects of market integration: Evidence from renewable energy expansion in Chile. Econometrica 91, 1659–1693.

Guan, Y., Yan, J., Shan, Y., Zhou, Y., Hang, Y., Li, R., Liu, Y., Liu, B., Nie, Q., Bruckner, B., et al., 2023. Burden of the global energy price crisis on households. Nature Energy 8, 304–316.

Gugler, K., Haxhimusa, A., Liebensteiner, M., 2018. Integration of European electricity markets: Evidence from spot prices. The Energy Journal 39.

Gugler, K., Heim, S., Jansen, M., Liebensteiner, M., 2023. Incumbency advantages: Price dispersion, price discrimination and consumer search at online platforms. Journal of Political Economy Microeconomics 1.

Gugler, K., Liebensteiner, M., Schmitt, S., 2017. Vertical disintegration in the european electricity sector: Empirical evidence on lost synergies. International Journal of Industrial Organization 52, 450–478.

Hintermann, B., 2016. Pass-through of co2 emission costs to hourly electricity prices in Germany. Journal of the Association of Environmental and Resource Economists 3, 857–891.

Hirth, L., 2013. The market value of variable renewables. The effect of solar wind power variability on their relative price. Energy Economics 38, 218 – 236.

Holladay, J.S., LaRiviere, J., 2017. The impact of cheap natural gas on marginal emissions from electricity generation and implications for energy policy. Journal of Environmental Economics and Management 85, 205–227.

Hu, J., Harmsen, R., Crijns-Graus, W., Worrell, E., van den Broek, M., 2018. Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design. Renewable and Sustainable Energy Reviews 81, 2181–2195.

IETA, 2022. GHG market sentiment survey 2022.

investing.com, 2023a. Carbon emissions futures. www.investing.com/commodities/carbon-emissions, accessed on June 1, 2023.

investing.com, 2023b. ICE Dutch TTF Natural Gas Futures. www.investing.com/commodities/ice-dutch-ttf-gas-c1-futures, accessed on June 1, 2023.

Jarvis, S., Deschenes, O., Jha, A., 2022. The private and external costs of Germany's nuclear phase-out. Journal of the European Economic Association 20, 1311–1346.

Kaufman, N., Barron, A.R., Krawczyk, W., Marsters, P., McJeon, H., 2020. A near-term to net zero alternative to the social cost of carbon for setting carbon prices. Nature Climate Change 10, 1010—-1014.

Kern, T., Ganz, K., Wasmeier, L., 2023. German electricity prices on the EPEX spot exchange in 2022. FfE, January 20, www.ffe.de/en/publications/german-electricity-prices-on-the-epex-spot-exchange-in-2022/.

Kosch, M., Blech, K., Abrell, J., 2023. Rising electricity prices in Europe: The impact of fuel and carbon prices. SSRN 4259209.

Kyllmann, C., 2012. Wind power expansion in Germany too slow. Clean Energy Wire, 28 Oct, www.cleanenergywire.org/news/wind-power-expansion-germany-too-slow-reporta.

Lazkano, I., Nøstbakken, L., Pelli, M., 2017. From fossil fuels to renewables: The role of electricity storage. European Economic Review 99, 113–129.

Lepesant, G., 2023. Higher renewable energy targets in Germany: How will the industry benefit? IFRI Center for Energy and Climate.

Liebensteiner, M., Haxhimusa, A., Naumann, F., 2023. Subsidized renewables' adverse effect on energy storage and carbon pricing as a potential remedy. Renewable and Sustainable Energy Reviews 171, 112990.

Liebensteiner, M., Naumann, F., 2022. Can carbon pricing counteract renewable energies' cannibalization problem? Energy Economics 115, 106345.

Lòpez Prol, J., Steininger, K.W., Zilberman, D., 2021. The cannibalization effect of wind and solar in the California wholesale electricity market. Energy Economics 85, 104552.

Maciejowska, K., 2020. Assessing the impact of renewable energy sources on the electricity price level and variability–a quantile regression approach. Energy Economics 85, 104532.

Mays, J., 2021. Missing incentives for flexibility in wholesale electricity markets. Energy Policy 149, 112010.

Mydland, Ø., Kumbhakar, S.C., Lien, G., Amundsveen, R., Kvile, H.M., 2020. Economies of scope and scale in the norwegian electricity industry. Economic Modelling 88, 39–46.

Newbery, D., Pollitt, M.G., Ritz, R.A., Strielkowski, W., 2018. Market design for a high-renewables European electricity system. Renewable and Sustainable Energy Reviews 91, 695–707.

Olea, J.L.M., Pflueger, C., 2013. A robust test for weak instruments. Journal of Business & Economic Statistics 31, 358–369.

Palzer, A., Henning, H.M., 2014. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies–part ii: Results. Renewable and Sustainable Energy Reviews 30, 1019–1034.

Proctor, D., 2023. Poland moves forward with country's first nuclear power plant. February 22, www.powermag.com/poland-moves-forward-with-countrys-first-nuclear-power-plant/.

Prognos, 2022. Strompreisprognose. Study commissioned by the Bavarian Industry Association (vbw – Vereinigung der Bayerischen Wirtschaft) www.vbw-bayern.de/Redaktion/Frei-zugaengliche-Medien/Abteilungen-GS/Wirtschaftspolitik/2022/Downloads/vbw_Strompreisprognose.pdf.

Reuters, 2022. Netherlands plans to build two nuclear power plants by 2035. December 9, www.reuters.com/business/energy/netherlands-plans-build-two-nuclear-power-plants-by-2035-2022-12-09/.

Ruhnau, O., Stiewe, C., Muessel, J., Hirth, L., 2023. Natural gas savings in Germany during the 2022 energy crisis. Nature Energy 8, 1–8.

Ruibal, C.M., Mazumdar, M., 2008. Forecasting the mean and the variance of electricity prices in deregulated markets. IEEE Transactions on Power Systems 23, 25–32.

Sasse, J.P., Trutnevyte, E., 2020. Regional impacts of electricity system transition in Central Europe until 2035. Nature Communications 11, 4972.

Schmitt, A., 2022. Eu energy outlook 2050: How will the european electricity market develop over the next 30 years? Energy Brainpool, April 11, blog.energybrainpool.com/en/eu-energy-outlook-2050-how-will-the-european-electricity-market-develop-over-the-next-30-years/.

Schäffer, L.E., Mo, B., Graabak, I., 2019. Electricity prices and value of flexible generation in northern Europe in 2030, in: 2019 16th International Conference on the European Energy Market (EEM), IEEE. pp. 1–6.

Shah, I., Iftikhar, H., Ali, S., 2022. Modeling and forecasting electricity demand and prices: A comparison of alternative approaches. Journal of Mathematics 2022.

Silva-Rodriguez, L., Sanjab, A., Fumagalli, E., Virag, A., Gibescu, M., 2022. Short term wholesale electricity market designs: A review of identified challenges and promising solutions. Renewable and Sustainable Energy Reviews 160, 112228.

Simon, F., 2021. Analyst: EU carbon price on track to reach €90 by 2030. Euractive, 19 July, www.euractiv.com/section/emissions-trading-scheme/interview/analyst-eu-carbon-price-on-track-to-reach-e90-by-2030/.

Solarin, S.A., Bello, M.O., 2021. Output and substitution elasticity estimates between renewable and non-renewable energy: Implications for economic growth and sustainability in india. Environmental Science and Pollution Research 28, 65313–65332.

Stevens, P., 2022. Prime minister Boris Johnson says the UK will build one new nuclear plant a year. CNBC, May 2, www.cnbc.com/2022/05/02/boris-johnson-uk-will-build-one-new-nuclear-plant-a-year.html.

Sun, H., Edziah, B.K., Kporsu, A.K., Sarkodie, S.A., Taghizadeh-Hesary, F., 2021. Energy efficiency: The role of technological innovation and knowledge spillover. Technological Forecasting and Social Change 167, 120659.

Thimet, P.J., Mavromatidis, G., 2022. Review of model-based electricity system transition scenarios: An analysis for Switzerland, Germany, France, and Italy. Renewable and Sustainable Energy Reviews 159, 112102.

Tschora, L., Pierre, E., Plantevit, M., Robardet, C., 2022. Electricity price forecasting on the day-ahead market using machine learning. Applied Energy 313, 118752.

Västermark, K.L., Hofmann, M., Bergmann, E., Kringstad, A., 2015. A european energy-only market in 2030. Statnett SF, Oct, Report.

Wang, D., Gryshova, I., Kyzym, M., Salashenko, T., Khaustova, V., Shcherbata, M., 2022a. Electricity price instability over time: Time series analysis and forecasting. Sustainability 14, 9081.

Wang, P., Xu, K., Ding, Z., Du, Y., Liu, W., Sun, B., Zhu, Z., Tang, H., 2022b. An online electricity market price forecasting method via random forest. IEEE Transactions on Industry Applications 58, 7013–7021.

Welisch, M., Ortner, A., Resch, G., 2016. Assessment of RES technology market values and the merit-order effect: An econometric multi-country analysis. Energy & Environment 27, 105–121.

Wettengel, J., 2023. Draft update to Germany's hydrogen strategy sees higher 2030 demand. Clean Energy Wire, 6 March, www.cleanenergywire.org/news/draft-update-germanys-hydrogen-strategy-sees-higher-2030-demand-media.

Xiang, C., Zheng, X., Song, F., Lin, J., Jiang, Z., 2023. Assessing the roles of efficient market versus regulatory capture in china's power market reform. Nature Energy .

Zarnikau, J., Tsai, C., Woo, C.K., 2020. Determinants of the wholesale prices of energy and ancillary services in the US midcontinent electricity market. Energy 195, 117051.

Zhuo, Z., Du, E., Zhang, N., Nielsen, C.P., Lu, X., Xiao, J., Wu, J., Kang, C., 2022. Cost increase in the electricity supply to achieve carbon neutrality in china. Nature Communications 13, 3172.

Appendix

Table A1: Regression estimates: second stage

Variable	Coef.		Std. Err.	p-value	[95% Conf.	Interval]
R	-0.002894	***	0.0002018	0	-0.0032896	-0.0024985
R·R	-1.87E-08	***	1.52E-09	0	-2.17E-08	-1.57E-08
P_{CO2}	0.1012536		0.1358644	0.456	-0.1650358	0.367543
$P_{CO2} \cdot P_{CO2}$	0.0070137	***	0.0011217	0	0.0048153	0.0092121
P_{gas}	1.062423	***	0.0834362	0	0.8988912	1.225955
$P_{gas} \cdot P_{gas}$	0.0022737	***	0.0003456	0	0.0015964	0.002951
L	-0.0013408	***	0.0002697	0	-0.0018694	-0.0008123
L·L	3.37E-08	***	2.45E-09	0	2.89E-08	3.85E-08
N	-0.009474	***	0.0009325	0	-0.0113017	-0.0076464
N· N	3.13E-07	***	4.48E-08	0	2.25E-07	4.01E-07
$\widehat{EX}$	0.0059821	***	0.0004966	0	0.0050088	0.0069554
FE hours of day	✓					
FE days of week	✓					
FE months of year	✓					
FE years	✓					
Observations	73,432					
R^2	0.8324					
Effective first-stage F stat.	875.22					

Dependent variable: day-ahead electricity spot price in €/MWh.
Sample period: 1jan2015–31may2023, hourly frequency.
Instrumented for EX by WFR
R … Renewable energy infeed (MWh)
P_{CO2} *… Emission allowance price (EUA) (€/tCO_2)*
P_{gas} *… Price of natural gas (€/MWh)*
L … Load, day-ahead forecast (MWh)
N … Nuclear energy infeed (MWh)
EX … Net Exports (MWh) – prediction from first-stage
Heteroscedasticity and autocorrelation consistent (HAC) standard errors are applied.
**** p<1%, ** p<5%, * p<10%*

Table A2: Regression estimates: first stage

Variable	Coef.		Std. Err.	p-value	[95% Conf.	Interval]
WFR	-0.1947696	***	0.0065836	0	-0.2076734	-0.1818657
R	0.3667799	***	0.0056498	0	0.3557063	0.3778535
R·R	-5.18E-07	***	9.68E-08	0	-7.07E-07	-3.28E-07
P_{CO2}	11.26118		8.901707	0.206	-6.186131	28.70849
$P_{CO2} \cdot P_{CO2}$	0.0936688		0.0683676	0.171	-0.0403316	0.2276691
P_{gas}	22.45333	***	2.088824	0	18.35924	26.54741
$P_{gas} \cdot P_{gas}$	-0.0594545	***	0.0071356	0	-0.0734402	-0.0454689
L	-0.0025611		0.0202965	0.9	-0.0423422	0.0372199
L·L	-7.40E-07	***	1.74E-07	0	-1.08E-06	-3.99E-07
N	1.493632	***	0.0528412	0	1.390064	1.597201
N·N	-0.0000552	***	3.19E-06	0	-0.0000614	-0.0000489
FE hours of day	✓					
FE days of week	✓					
FE months of year	✓					
FE years	✓					
Observations	73,432					
Effective first-stage F stat.	875.22					

Dependent variable: net exports in MWh. Sample period: 1jan2015–31may2023, hourly frequency.
WFR … Wind energy infeed in France (MWh)
R … Renewable energy infeed (MWh)
P_{CO2} … Emission allowance price (EUA) (€/tCO_2)
P_{gas} … Price of natural gas (€/MWh)
L … Load, day-ahead forecast (MWh)
N … Nuclear energy infeed (MWh)
Heteroscedasticity and autocorrelation consistent (HAC) standard errors are applied.
**** p<1%, ** p<5%, * p<10%*

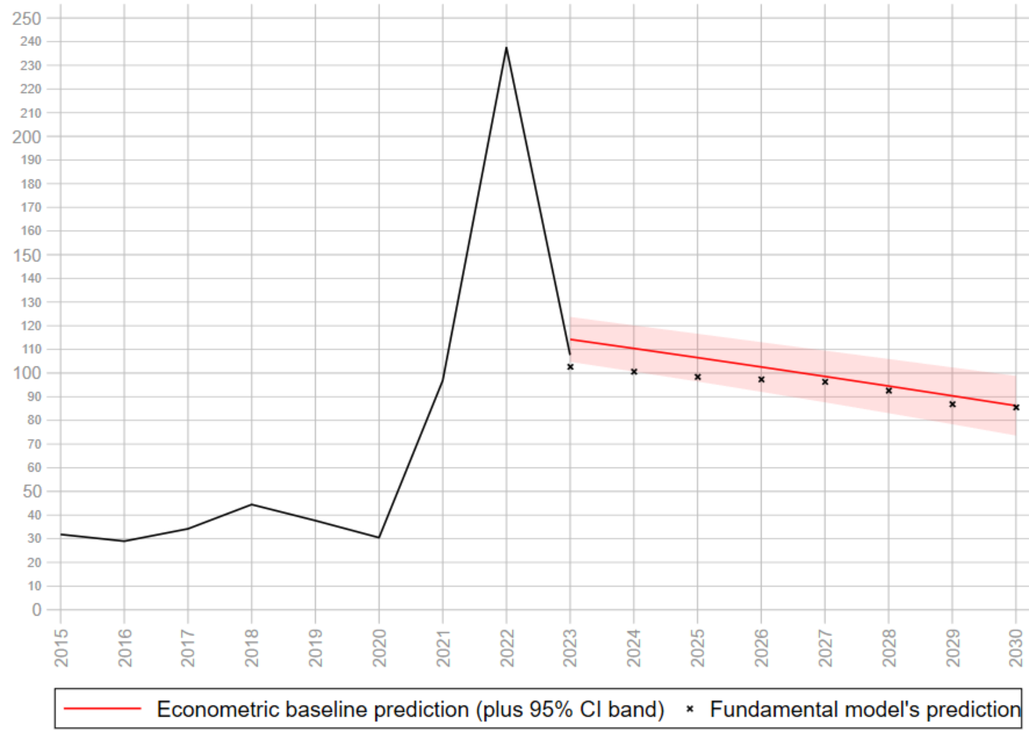


Figure A1: Robustness test: Electricity price projection from a fundamental model vs. econometric baseline scenario

The graph shows the predicted electricity wholesale price from a fundamental energy model (scatter) and the the econometric baseline scenario prediction (incl. the 95% confidence intervals) (line).