

Towards Cheaper Electricity

Moving Europe from Gas to Renewables

Jordi Schröder Bosch

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Executive Summary

The European Union (EU) remains vulnerable to fossil fuel price volatility and its negative implications for energy security, inflation, and competitiveness. In the current context of increased geopolitical volatility, the rapid expansion of renewable energy, particularly wind and solar, has emerged as a structural shift in most European countries.

Through this shift, many countries are starting to observe a decoupling of wholesale electricity prices from gas prices during hours of high renewable generation, exerting downward pressure on prices. In this report, we provide new cross-country evidence for a sample of euro area economies using high-frequency data. We estimate that **the deployment of wind and solar reduced wholesale electricity prices by an average of 24.2% over the period 2023–2025** across the countries analysed. These effects are nonlinear and increase with renewable penetration, reflecting stronger price impacts at higher levels of wind and solar deployment.

However, the decoupling of electricity prices from fossil fuel costs remains incomplete in most European electricity markets, as gas continues to act as the marginal price setter most of the time. As a result, wholesale electricity prices remain sensitive to fossil fuel shocks, particularly during periods of low renewable penetration.

Two key implications follow from these findings. First, in countries with low renewable energy penetration, accelerating the deployment of wind and solar is a low-hanging fruit for reducing wholesale electricity prices and vulnerability to fossil fuel shocks. In countries with already high renewable deployment, scaling up flexibility resources is key to sustain further price reductions, reinforce decoupling from fossil fuel shocks and enable additional integration of wind and solar generation. As we show, wind and solar deployment make the economics of flexibility resources highly attractive, facilitating the next stage of decoupling.

Ultimately, strengthening the interaction between renewable energy, flexibility, and electrification can generate two mutually reinforcing feedback loops. Greater deployment of wind and solar incentivises the deployment of flexibility resources, which, in turn, enable higher levels of renewable integration, further reinforcing price reductions. Second, this price reduction incentivises electrification across sectors. Rising electricity demand, especially from flexible uses, creates more room for renewable deployment, while simultaneously decoupling electrifying sectors from fossil fuels.

As these dynamics are key to strengthening Europe's resilience to fossil fuel shocks, policymakers must prioritise accelerating the deployment of renewable energy, flexibility resources, and electrification.

Introduction

Several of the major challenges that the European Union (EU) currently faces revolve around energy. The EU is highly dependent on imported fossil fuels,¹ making it vulnerable to fossil fuel shocks. This dependence poses great risks for **energy security and affordability**.² During 2022, the energy crisis caused by the Russian invasion of Ukraine led to the highest inflation on record in the euro area. This placed considerable strain on household finances, especially lower-income households.³ More recently, military escalation in the Middle East triggered by US-led actions against Iran has resulted in the closure of the Strait of Hormuz, through which about 20% of global oil consumption and 20% of traded liquefied natural gas (LNG) flows, further underlining this vulnerability.⁴

Exposure to volatile fossil fuels is a structural challenge for European **competitiveness**. During the 2022 energy crisis, electricity prices for the industrial sector in the EU were 172% higher than in the United States, creating a cost disadvantage for European firms.⁵ Since the recent escalation in the Middle East, natural gas prices in the EU have increased by 57%, compared with roughly 10% in the United States. This creates a clear cost disadvantage for European firms, especially energy intensive ones.

In recent years, the deployment of renewable energy sources—especially solar, and to a lesser extent wind—has accelerated in most European countries. Understanding how renewable energy affects electricity prices is therefore crucial for assessing the role of the energy transition in addressing these challenges.

A growing body of research has examined the impact of renewable energy on wholesale electricity prices, finding that increased wind and solar penetration exerts downward pressure by displacing higher-cost fossil fuel generation.⁶ These studies provide aggregate estimates for Europe or focus on single-country analyses. In this study, we provide new cross-country evidence for a sample of euro area countries. Given the heterogeneity of electricity systems across Europe, our approach captures how these differences shape the impact of renewable penetration on wholesale electricity prices. We find that the expansion of renewable generation has reduced electricity prices by an average of 24.2% over the 2023–2025 period in the sample of countries analysed, with large variation across countries.

However, the decoupling of electricity prices from gas prices remains at an early stage in many European electricity systems. Our findings therefore underline the importance of wind and solar deployment, which, together with flexibility resources, can largely reduce Europe's electricity markets' exposure to fossil fuel shocks. By doing so, this process makes the electrification of the economy more attractive, further reducing Europe's vulnerability to fossil fuels.

The report proceeds as follows. Section 2 outlines recent developments in European electricity markets. Section 3 presents the empirical analysis of the impact of wind and solar on wholesale electricity prices. Section 4 discusses policy challenges and the way forward, and the final section concludes.

1. [ACER \(2026\). Key developments in EU electricity and gas markets](#)

2. [European Commission \(2022\): RePowerEU Plan; European Commission \(2025\). Action Plan for Affordable Energy: Unlocking the true value of our Energy Union to secure affordable, efficient and clean energy for all Europeans](#)

3. [Bobasu et al. \(2023\). The impact of the recent inflation surge across households](#)

4. Some forecasts point to TTF moving towards 90 €/MWh if direct Qatari LNG exports are removed considering the tightening global LNG balance. See: [ICIS \(2026\): Potential Strait of Hormuz closure could push Europe's TTF gas benchmark above €90.00/MWh](#)

5. [ACER \(2026\). Key developments in EU electricity and gas markets](#)

6. [Cevik & Ninomiya \(2022\). Chasing the Sun and Catching the Wind: Energy Transition and Electricity Prices in Europe, IMF; Cubero et al. \(2025\). Reaping the Benefits of Renewable Energy in the Spanish Economy; Herczeg & Pintér \(2024\). The Nexus between Wholesale Electricity Prices and the Share of Electricity Production from Renewables; IEA \(2023\). How much money are European consumers saving thanks to renewables?; IEA \(2025\). Renewables 2025; Quintana \(2024\). The impact of renewable energies on wholesale electricity prices. Banco de España.](#)

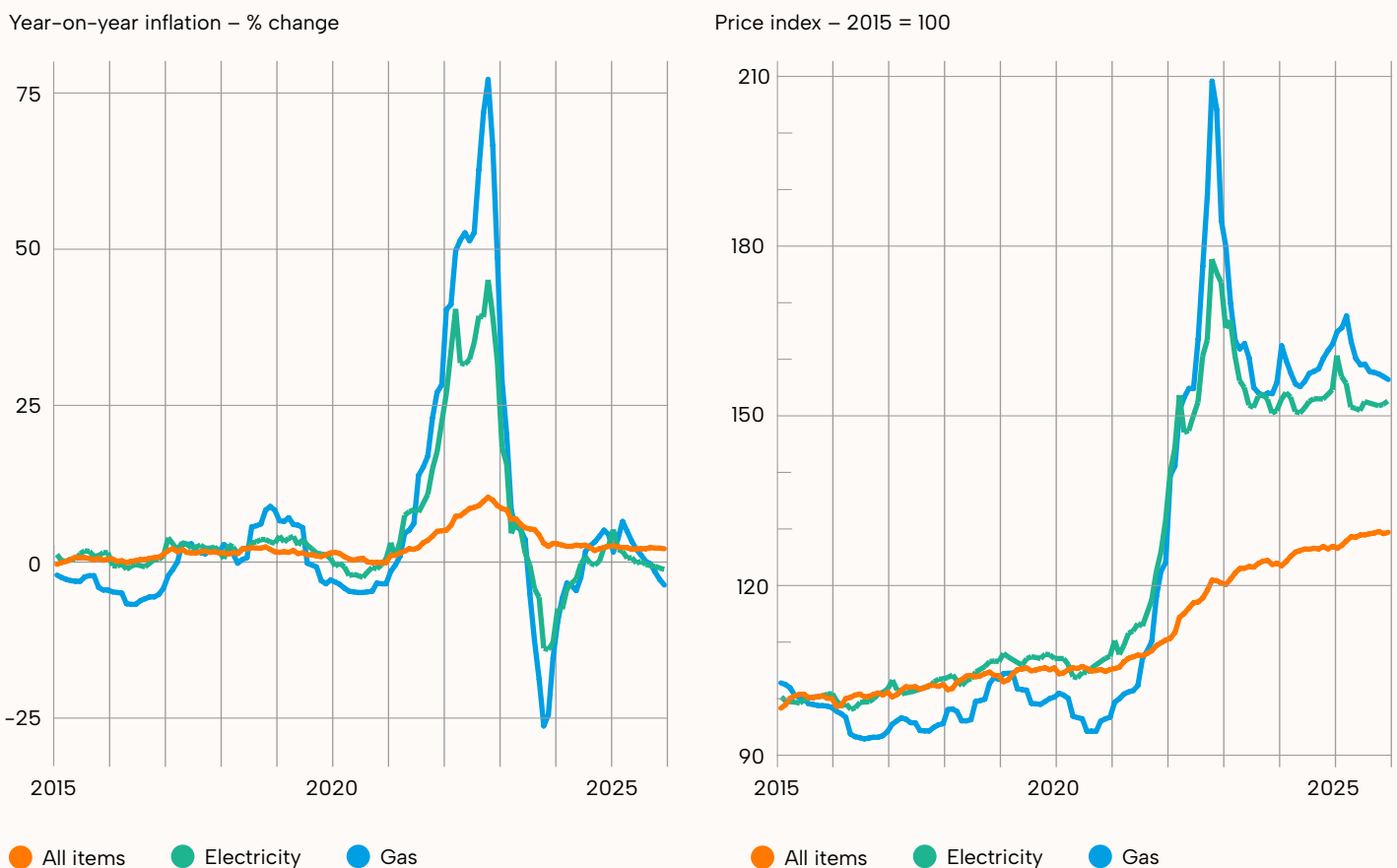
1. Recent developments in European electricity markets

Before turning to the main empirical analysis, this section outlines several stylised facts and recent developments in European electricity markets.

A. The 2022–2023 energy price shock

The 2022–2023 energy shock illustrated the risks that fossil fuel dependence poses to price stability. Natural gas prices skyrocketed after the Russian invasion of Ukraine, with the Dutch TTF hub peaking at around 340 €/MWh in 2022. This surge in gas prices translated into higher electricity prices and was the main driver of the inflation surge, which peaked at 10.6% in October 2022 (Figure 1, left panel), with countries more dependent on natural gas experiencing stronger inflation.⁷

Figure 1: Euro area HICP: year-on-year inflation (left) and price index (right) (2015–2026)



Source: Eurostat. Own elaboration.

Although energy price inflation declined after late 2022, electricity and gas prices remain elevated by historical standards (Figure 1, right panel), continuing to exert pressure on the finances of both households and firms. The ongoing military escalation in the Middle East, and its severe impacts on energy infrastructure, have triggered a rise in LNG prices. This unfolding fossil fuel shock will put upward pressure on electricity prices in Europe by

7. [Alessandri & Gazzani \(2025\). Natural gas and the macroeconomy: Not all energy shocks are alike](#); [Alvarez & Kroen \(2025\). The Energy Origins of the Global Inflation Surge](#)

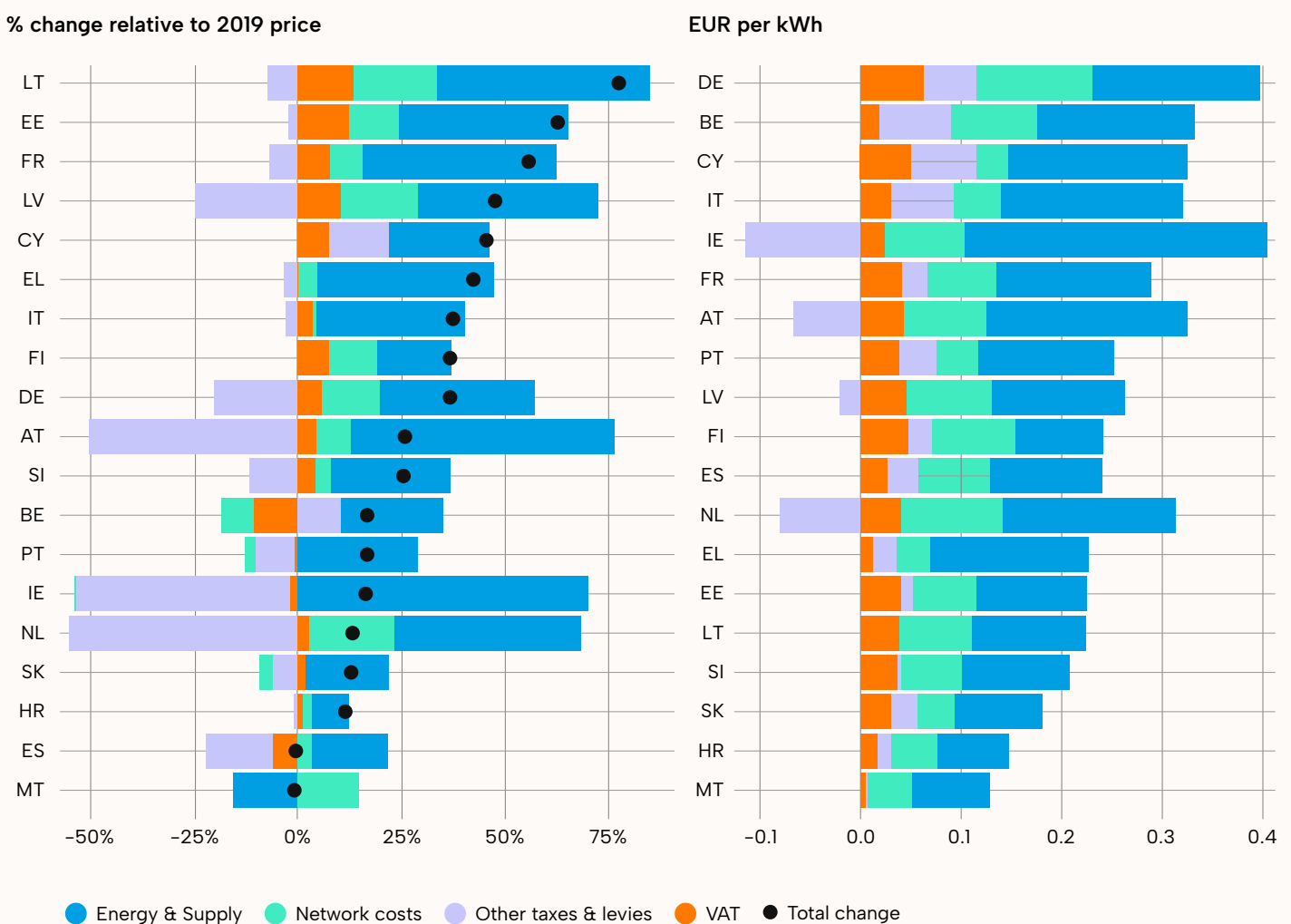
increasing natural gas prices, which are set in global markets and play a key role in setting electricity prices, as we discuss below.

B. The structure of electricity prices

Retail electricity prices consist of several components, including energy and supply costs, network charges, value-added tax (VAT), and other taxes and levies. The importance of each component differs across Euro area electricity markets (Figure 2, right panel).

However, the energy component has been the key driving force in rising retail electricity prices across those different countries between 2019 and 2024 (Figure 2, left panel). This motivates the focus of the present report on wholesale electricity markets.

Figure 2: Electricity price increase and component contributions (2019–2024) (left) and residential price decomposition by component (2024) (right)

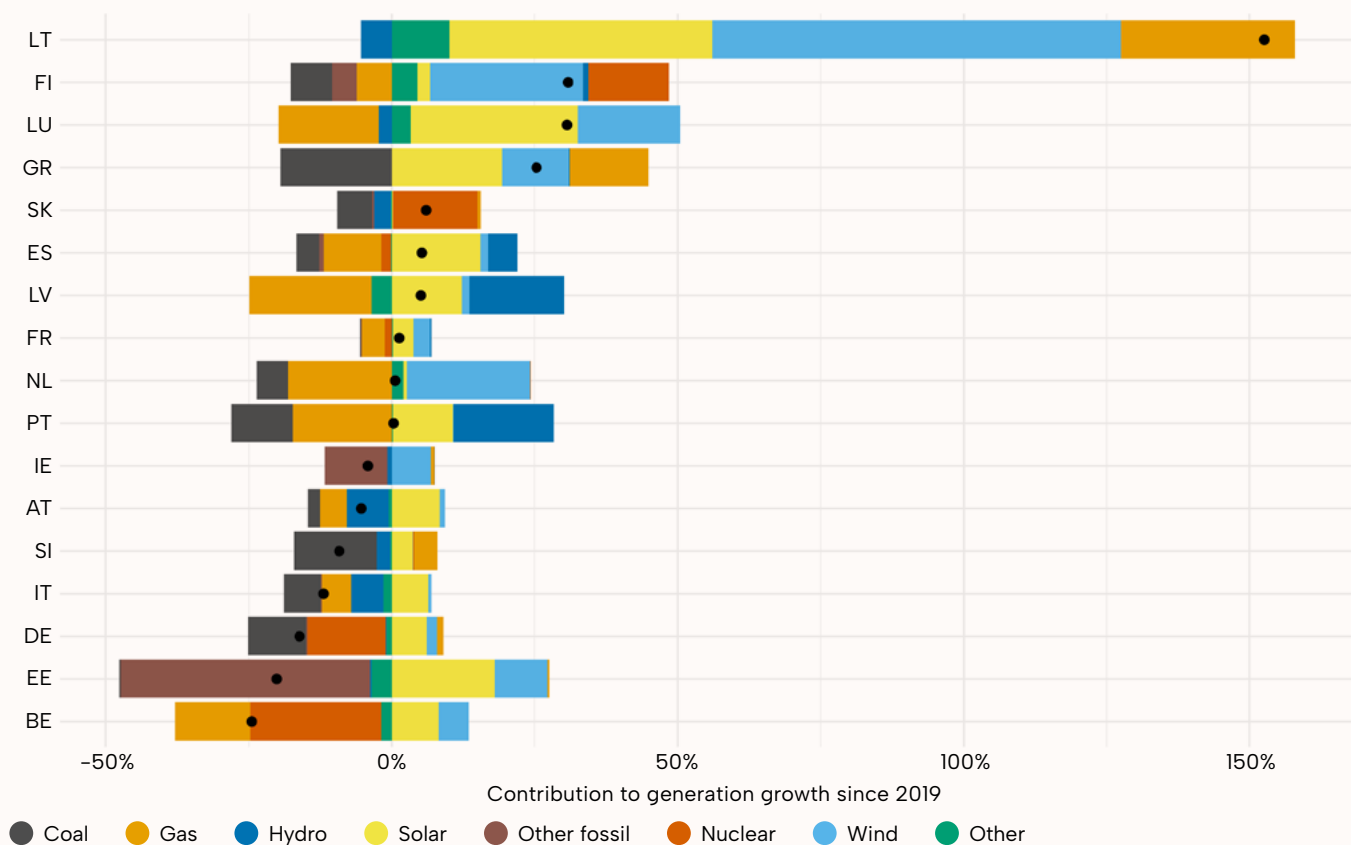


Source: Eurostat. Own elaboration.

Rising electricity prices have important distributional consequences: in the euro area, the poorest income decile spent more than 5% of disposable income on electricity in 2022, compared with just over 1% for the richest decile.⁸

8. Source: Eurostat (icw_aff_01).

Figure 4: Contribution of technologies to electricity generation growth (2019–2025)



Source: ENTSO-E. Own elaboration.

D. Gas as the marginal price setter: signs of decoupling

Despite the growing role of wind and solar and the gradual displacement of gas, the latter continues to play a central role in electricity price formation. European electricity markets operate under a merit-order mechanism, in which power plants are dispatched according to their marginal costs. The most expensive unit required to meet electricity demand sets the wholesale electricity price, irrespective of the share of demand it covers.

Gas-fired power plants typically act as the marginal unit—the one setting the price—in European electricity markets, owing to their higher marginal costs.¹⁰ This is also the case for countries where gas plays a marginal role in their electricity mix, such as Austria and France (see Figure 3), due to the role of interconnection in European electricity markets.¹¹

As a result, fluctuations in natural gas prices continue to exert a strong influence on electricity prices. However, the prominence of gas in price formation has decreased in some countries over recent years. This decoupling tendency can be observed in Figure 5 for some countries. For example, in France and Spain, the correlation between gas prices and wholesale electricity prices was very strong in 2018 (Figure 5, red dots). By 2025, this correlation weakens, and wholesale electricity prices are often below the level implied by gas costs, reflecting the growing penetration of renewable generation. This pattern is not observed in Italy due to its continued reliance on gas, which continues to anchor wholesale electricity prices.

10. ACER (2025). *Key developments in EU electricity and gas markets*; ACER (2026). *Key developments in EU electricity and gas markets*; Gasparella, Koolen & Zucker (2023). *The Merit Order and Price-Setting Dynamics in European Electricity Markets*, European Commission; Zakeri et al. (2023). *The role of natural gas in setting electricity prices in Europe*.

11. Gasparella, Koolen & Zucker (2023). *The Merit Order and Price-Setting Dynamics in European Electricity Markets*, European Commission

Figure 5: Daily wholesale electricity prices and gas prices



Source: ENTSO-E. Own elaboration.

Notes: Each point represents a day. Gas short-run marginal costs (SRMC) are computed as fuel costs divided by thermal efficiency, plus CO₂ costs based on emissions intensity, and a small variable operating cost.¹²

E. Renewable energy and wholesale electricity prices

The decoupling that is observed in Figure 5 is the result of increased renewable energy capacity, mainly wind and solar, which have very low marginal costs. There are two main channels through which renewable penetration reduces electricity prices. First, increased renewable generation leads to the most expensive marginal units being displaced. As a result, even when natural gas remains the price-setting technology, renewable generation pushes the most expensive gas power plants out of the market, lowering wholesale electricity prices. Second, when renewable sources cover total demand, they effectively set the marginal price, which is significantly below other technologies given their near-zero variable costs.¹³

Figure 6 shows that, as the share of demand covered by wind and solar increased between 2018 and 2025, electricity prices declined on days with higher renewable penetration.

12. See: [Rosslowe & Petrovich \(2026\): Latest energy shock reminds Europe of its risky gas reliance.](#)

13. [Cubero et al. \(2025\). Reaping the Benefits of Renewable Energy in the Spanish Economy](#)

Figure 6: Daily wholesale electricity prices and renewable share



Source: ENTSO-E. Own elaboration.

Notes: Each point represents a day.

The rapid expansion of renewable generation therefore has the potential to weaken the link between fossil fuel prices and electricity prices. However, the magnitude of this effect varies across countries and depends on the structure of national electricity systems. The next section presents estimates of the impact of renewable deployment on wholesale electricity prices across a group of euro area economies.

2. The impact of wind and solar on wholesale electricity prices

To quantify the impact of renewable generation on wholesale electricity prices, we follow the approach applied by Quintana.¹⁴ Using hourly data from ENTSO-E, our analysis proceeds in two steps. First, we estimate the variation in wholesale electricity prices explained by traditional cost determinants, in particular gas and CO₂ prices. This reflects the merit-order mechanism, whereby gas-fired power plants are the main price setters in European electricity markets.

Second, we analyse how residual electricity prices—deviations from those predicted by fundamental cost determinants—vary with the share of electricity demand covered by wind and solar generation in each country. The relationship between wind and solar generation and deviations from predicted prices is nonlinear (Figure 1A Annex).

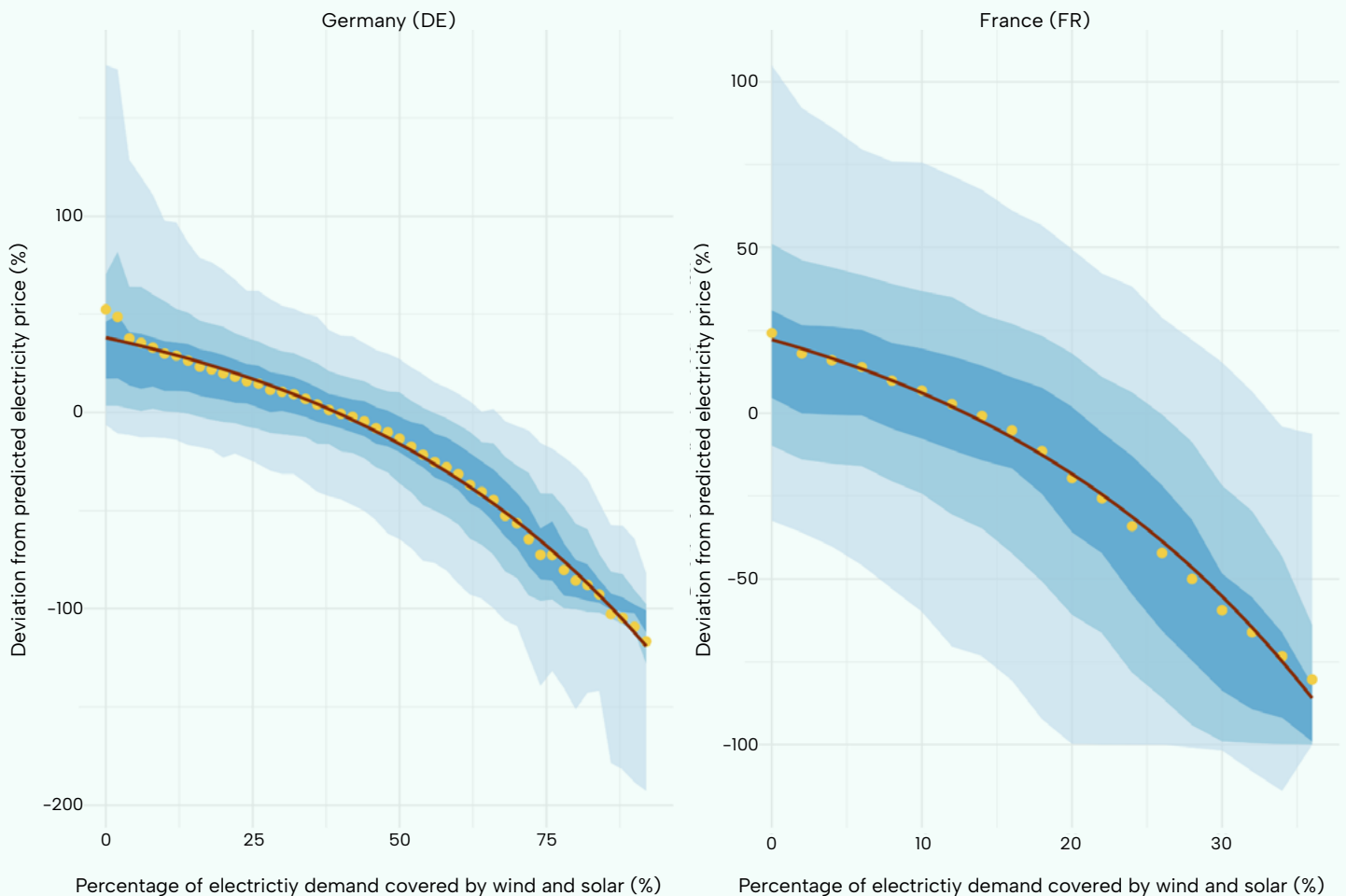
This is illustrated in Figure 7 for Germany and France. Germany has reached very large levels of renewable capacity, which lead to nonlinear effects when these technologies are the main generation source. Increasing renewable penetration from 10% to 25% is associated with a moderate reduction of wholesale electricity prices of about 14 percentage points, whereas a similar increase at higher levels (60% to 75%) leads to a much larger reduction of around 34 percentage points (Figure 7, left).

However, in some countries, nonlinear effects emerge at lower levels of renewable penetration, such as Austria and France. In these cases, the relationship between renewable penetration and wholesale electricity prices is strongly nonlinear. This reflects the higher share of lower marginal cost generation, particularly nuclear in France and both hydro and nuclear in Austria. Since gas plays a more marginal role in these countries, lower levels of renewable penetration are needed to displace it.

In France, increasing renewable penetration from 10% to 20% reduces prices by roughly 16 percentage points, while an increase from 25% to 35% leads to a very large reduction of about 45 percentage points (Figure 7, right).

14. Quintana (2024). *The impact of renewable energies on wholesale electricity prices*. Banco de España.

Figure 7: Relationship between renewable electricity share and price deviations (France and Germany)



Source: ENTSO-E. Own elaboration.

Notes: The figure shows the relationship between the share of electricity demand covered by wind and solar generation and deviations from traditional price determinants. Dots represent bin averages. Shaded areas show the distribution of residuals within bins: the darkest band corresponds to the 35th–65th percentiles, the medium band to the 20th–80th percentiles, and the lightest band to the 5th–95th percentiles. The solid line represents the fitted relationship.

Finally, the estimated relationship between renewable penetration and wholesale electricity prices (brown line, Figure 7 and Figure 1A in the Annex) is used to simulate counterfactual electricity prices under alternative scenarios for each country.¹⁵ These counterfactuals allow us to quantify the impact of renewable penetration on wholesale electricity prices.

The results in Figure 8 clearly show that renewable generation has led to substantial reductions in wholesale electricity prices across the sample of Euro area countries. Two main patterns stand out. First, the magnitude of the price effect increases over time, as wind and solar capacity has expanded.

Second, as mentioned above, the composition and structure of the electricity system matter. In France, despite relatively lower wind and solar capacity compared to Spain or Germany, the estimated price effects are significant. With nuclear playing a more prominent role, less renewable penetration is needed to decouple

15. As discussed in the Annex, Ireland and Lithuania do not exhibit an exponential relationship. In both cases, the relationship between renewable penetration and price deviations is therefore modelled using a linear specification.

electricity prices from gas and hence lead to price reductions. In contrast, countries with a stronger reliance on gas-fired generation and more limited renewable expansion, such as Italy or Ireland, exhibit smaller and more stable effects over time.

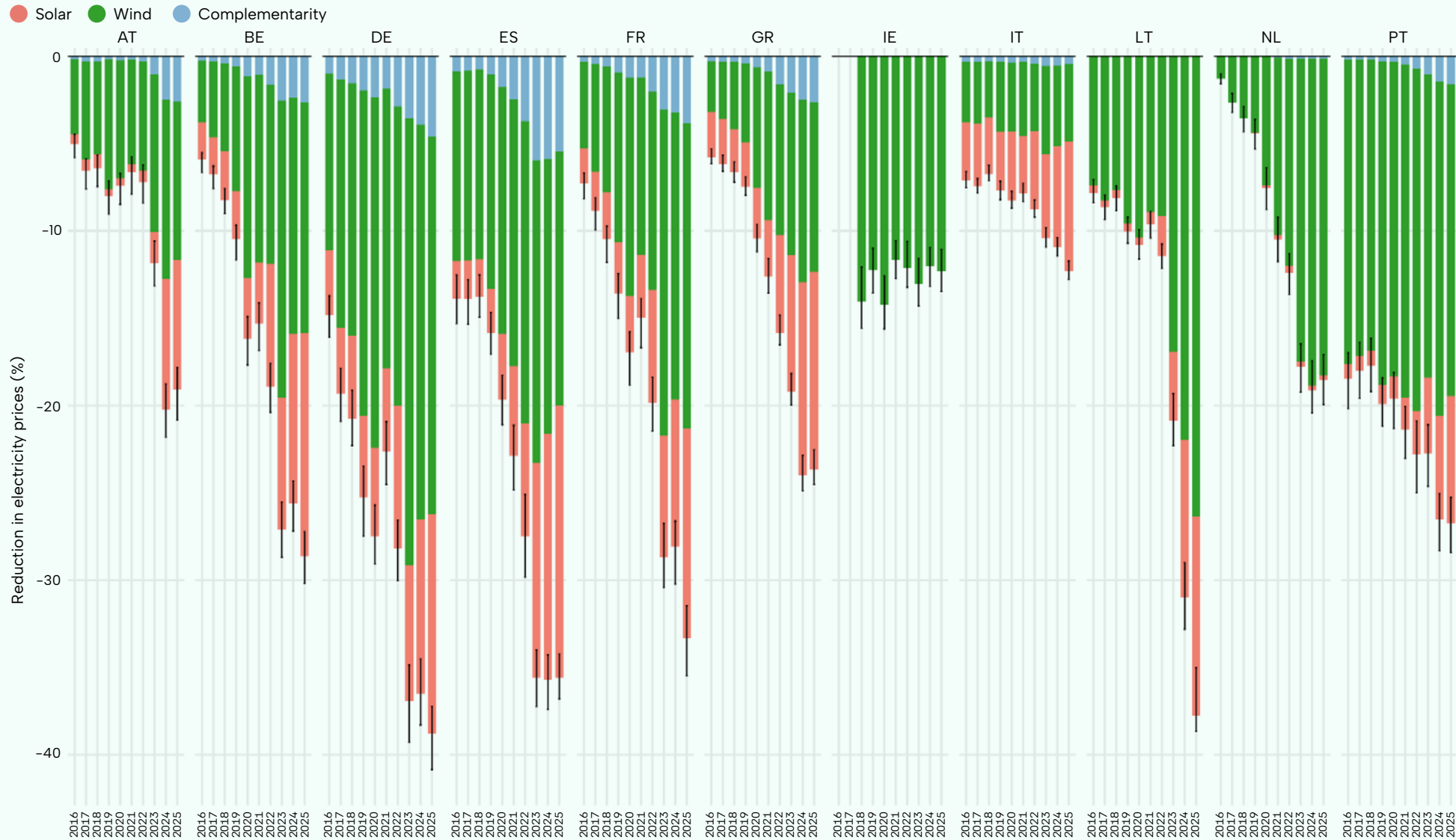
Wind generation accounts for the largest share of price reductions in most countries, reflecting its higher average contribution to total generation. However, the results show a significant and increasingly larger effect of solar, as its deployment has accelerated with respect to wind in recent years, especially for countries like Spain or Greece.¹⁶ At the same time, in countries where both technologies have large levels of capacity, we observe significant complementarity effects, since periods in which both technologies generate simultaneously lead to larger price reductions than the sum of their individual effects.

There is also heterogeneity in trends across countries. For example, Lithuania shows a sharp increase in price effects in recent years, driven by the rapid deployment of wind and solar. Conversely, countries such as Ireland and Italy exhibit more moderate and stable effects over time.

Finally, while the estimated effects are large, they are subject to uncertainty, as reflected in the confidence intervals shown in Figure 8. Nevertheless, the results consistently indicate that renewable generation has played a key role in reducing wholesale electricity prices across European electricity markets.

16. [IEA \(2025\). Renewables 2025](#)

Figure 8: Estimated impact of wind and solar generation on electricity prices



Source: ENTSO-E. Own elaboration.

Notes: Black bars indicate 95% confidence intervals for the total effect, obtained via bootstrap resampling.

3. Policy challenges and the way forward

As we have seen in the previous section, the deployment of wind and solar has led to an increasing decoupling of wholesale electricity prices from those implied by traditional determinants. However, in the absence of flexibility resources, there are limits to the extent to which wind and solar can reduce wholesale electricity prices. In countries where renewable penetration is already high, such as Spain or Germany, further capacity additions, if not complemented by flexibility resources, are likely to generate diminishing downward effects on prices; that is, their price-reducing impact will be attenuated.

This happens because wind and solar are variable generation sources that depend on weather conditions. Beyond a certain point, additional generation is more likely to coincide with periods in which supply already exceeds system needs or where system constraints (such as transmission bottlenecks) bind, leading to curtailment. As a result, the downward impact on prices is concentrated during periods of high renewable output, especially peak solar hours (Figure 9), and is more limited in displacing gas outside these periods.

This is illustrated in Figure 9, which shows that low wholesale electricity prices are concentrated during peak solar hours, especially in sunnier months. By contrast, traditional cost determinants continue to set prices during morning and evening peaks, when demand is high and solar output is low.

Figure 9: Average hourly wholesale electricity price by month (2025)



Source: ENTSO-E. Own elaboration.

Therefore, system flexibility is a fundamental piece of the puzzle to enable further integration of renewable energy sources and reduce prices during peak hours. By increasing intraday price differences, wind and solar enhance the attractiveness of flexibility resources, which allow electricity supply and demand to be shifted across time, such as storage or demand flexibility.

Currently, in the sample of countries analysed in the previous section, there are 9.3 GW of installed battery power capacity (27 GWh of energy capacity) in operation, and 44.8 GW (173 GWh) in the pipeline (either announced, permitted, or under construction).¹⁷ While declining battery costs are an important driver of deployment,¹⁸ the intraday price variation created by wind and solar is also crucial, as battery economics rely on arbitrage between periods of low and high electricity prices.¹⁹

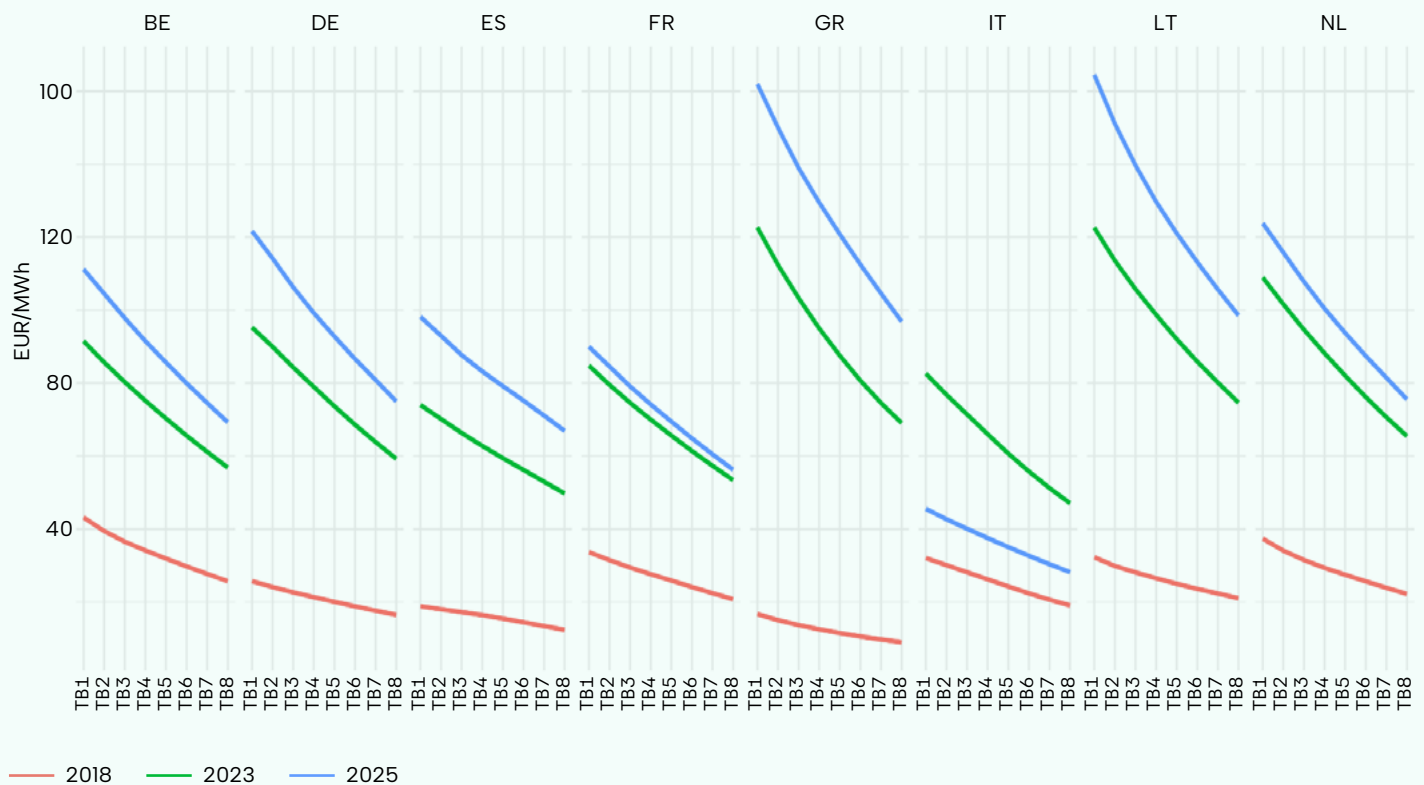
17. [European Commission \(2026\). European Energy Storage Inventory](#). Last accessed 12.03.2026.

18. [IRENA \(2025\). Renewable Power Generation Costs in 2024](#); [IEA \(2026\). Electricity 2026](#).

19. Other factors also play a key role for deployment, such as the availability of capacity payments or revenue from ancillary services. See: [IEA \(2024\). Batteries and Secure Energy Transitions](#).

Figure 10 shows the normalised annual average daily cumulative price difference between the highest and lowest hourly electricity prices (TB1–TB8). TB1 represents the average daily spread between the single highest and lowest hourly prices, while higher TB values extend this to the difference between the n highest and n lowest hourly prices (e.g. TB8 being the average daily difference between the eight highest and eight lowest hourly prices). Therefore, by increasing intraday price differences, increasing renewable penetration makes the economics of batteries more attractive. This can be seen in the upward shift and steepening of the TBn curves that has taken place over the recent years (Figure 10).

Figure 10: Normalised annual average daily cumulative price difference



Source: ENTSO-E. Own elaboration.

Furthermore, this intraday price variation creates incentives for demand-side flexibility. As electrification in sectors such as residential heating and transport advances, demand-side flexibility can play a key role in shifting electricity consumption away from peak hours towards periods of higher renewable penetration, when prices are lower, facilitating further integration of renewable energy sources.

The deployment of cheap renewable energy sources can create two interacting feedback loops.²⁰ First, by reducing prices during periods of high renewable penetration, wind and solar make batteries more attractive. Investment in storage then enables further integration of renewable energy, reinforcing downward pressure on electricity prices.

20. Sharpe et al (2025). System archetypes of the energy transition: Feedback loops and levers of change; Wilson et al. (2020). Granular technologies to accelerate decarbonization

Second, lower electricity prices incentivise the electrification of other sectors (e.g. transport and heating), increasing electricity demand, which allows for more integration of renewable and storage deployment, while also enabling a greater role for demand flexibility. Faster deployment, in turn, accelerates the downward cost trajectory of these technologies through economies of scale and learning-by-doing.²¹

Hence, while wind and solar face limits when deployed in isolation, they also incentivise the deployment of flexibility resources, which enable further decoupling of electricity prices from traditional cost determinants. Therefore, complementarities between the deployment of renewable energy, storage, and electrification have the potential to drive system-wide benefits. Policymakers have a key role to play in facilitating and incentivising the deployment of these technologies, which will accelerate these positive feedback loops.

21. [Speelman & Numata \(2024\). Harnessing the Power of S-Curves](#)

Conclusion

This study shows that wind and solar have played a significant role in reducing wholesale electricity prices across several euro area countries. On top of that, their deployment also creates incentives for flexibility resources, which, in turn, enable further price reductions beyond periods of high renewable generation.

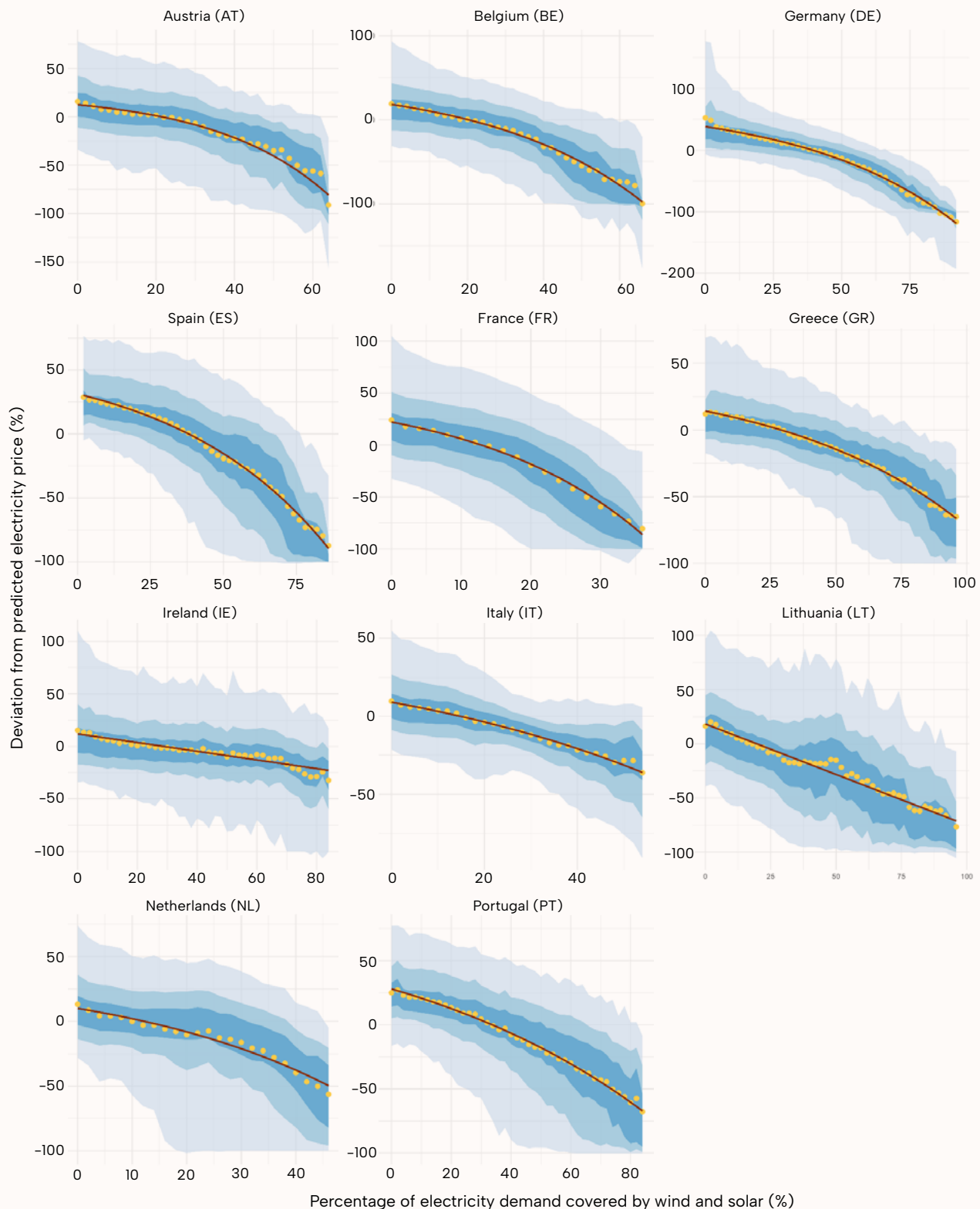
Two policy implications follow. In countries with limited wind and solar capacity, accelerating their deployment is a low-hanging fruit for reducing wholesale electricity prices. In countries with large wind and solar capacity, scaling up flexibility resources will further enable the decoupling of wholesale prices from traditional cost determinants.

The exposure of electricity prices to fossil fuel shocks complicates the electrification of the economy, which is a key pillar of the energy transition. However, accelerating these system-wide changes leads to the decoupling of electricity prices from fossil fuel shocks, which in turn supports further electrification. This creates an opportunity to reduce Europe's vulnerability to fossil fuel shocks beyond the electricity sector, extending to other fossil fuel-dependent activities such as transportation.

Ongoing events highlight the urgency to accelerate these trends. Continued fossil fuel shocks compromise Europe's energy security, price stability, and competitiveness, among others. In the absence of sufficiently rapid progress, Europe will remain subject to the multifaceted risks that fossil fuel dependency poses.

Annex A. Figures

Figure 1A: Relationship between renewable electricity share and price deviations



Source: ENTSO-E. Own elaboration.

Notes: The figure shows the relationship between the share of electricity demand covered by wind and solar generation and deviations from traditional price determinants. Dots represent bin averages. Shaded areas show the distribution of residuals within bins: the darkest band corresponds to the 35th-65th percentiles, the medium band to the 20th-80th percentiles, and the lightest band to the 5th-95th percentiles. The solid line represents the fitted relationship.

Annex B. Methodology

A. First stage estimation: traditional cost determinants

In the first step, we estimate the component of electricity prices explained by traditional cost determinants for each country. Hourly wholesale electricity prices are modelled as a function of gas and CO2 prices:

$$p_h = \alpha + \beta_1 gas_d + \beta_2 CO2_d + \varepsilon_h$$

where p_h denotes the electricity price in hour h , and gas_d and $CO2_d$ are daily gas and carbon prices.

This specification captures the component of electricity prices that can be explained by traditional cost determinants. This specification exploits the merit-order mechanism: even when gas-fired generation accounts for a smaller share of total generation, it often determines the wholesale electricity price.

The residual term ε_h therefore represents the component of electricity prices that cannot be explained by traditional cost determinants. In the context of electricity markets, this residual primarily reflects changes in the marginal generation technology, including the impact of renewable generation.

B. Second-stage estimation: renewable penetration and price deviations

In the second step, we estimate the relationship between electricity price deviations (ε_h) and renewable penetration (R_h). This relationship is nonlinear: increases in renewable penetration have a limited effect at low levels but lead to increasingly large price reductions as renewable output rises.

To capture this nonlinearity, we estimate an exponential functional form:

$$f(R) = ae^{br} + c$$

where $f(R)$ denotes the expected electricity price deviation associated with renewable penetration R_h .

Renewable penetration is grouped into 2-percentage point intervals (bins). For each bin, we compute the average residual electricity price and estimate the functional relationship using these aggregated observations. This results in a curve which displays the relationship between electricity price deviation from traditional cost fundamentals as renewable penetration increases.

For most countries, the estimated relationship is well approximated by the exponential specification described above. However, in the cases of Ireland and Lithuania, the relationship between renewable penetration and price deviations is approximately linear. Therefore, in those two cases a linear functional form is used instead. The estimated relationship for each country is illustrated in Figure 1A in the Annex.

C. Counterfactual price simulations

The estimated relationship $f(R_h)$ is used to simulate electricity prices under alternative renewable generation scenarios. For each hour, the model-implied electricity price is given by:

$$\tilde{p}_h = \hat{p}_h + f(R_h)$$

where \widehat{p}_h is the predicted electricity price from the first-stage regression and $f(R_h)$ is the estimated residual associated with renewable penetration R_h .

The observed electricity price corresponds to the case where renewable penetration equals the actual observed level R_h^{obs} :

$$p_h = \widehat{p}_h + f(R_h^{obs})$$

To quantify the contribution of wind and solar, the counterfactual analysis evaluates their effects separately by applying the estimated relationship to each technology's generation, as well as to their combined share. The difference between the combined effect and the sum of the individual effects is interpreted as the complementarity effect between solar and wind generation.

To construct a counterfactual scenario without renewable generation, we set renewable penetration equal to zero:

$$p_h^{noRES} = \widehat{p}_h + f(0)$$

The hourly price effects are then aggregated to the annual level to obtain the impact of renewable generation on wholesale electricity prices.

To assess the statistical uncertainty of the counterfactual scenario, confidence intervals are computed through bootstrapping, where the hourly data are resampled at the day level within year-month cells. For each bootstrap draw, the full estimation procedure is repeated. Confidence intervals are then constructed from the distribution of estimated annual effects across bootstrap samples.

It is important to note that this approach has some limitations. First, the residual used in the second stage captures all factors affecting electricity prices beyond conventional cost determinants. While renewable generation is a key driver, other factors may also contribute to the residual variation. Second, the relationship between renewable penetration and price deviations exhibits substantial dispersion. Hence, the estimated effects should be interpreted as statistical averages rather than precise hourly impacts. Finally, the counterfactual analysis represents a partial-equilibrium exercise that does not account for broader market adjustments that would occur in a system without renewables.



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