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How do domestic energy resources and transport constraints shape regional energy consumption and energy security in Europe?

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Abstract

This thesis[1] examines whether domestic energy resources protect European countries from fossil-fuel price shocks. Using panel data across 30 countries, we combine an annual energy-balance panel (2000 to 2023) with a wholesale electricity price panel (2015 to 2024). We study how domestic production shapes consumption and whether national energy mixes moderate gas-price pass-through. Fixed effects regressions show that gas prices strongly affect wholesale electricity prices regardless of nuclear or renewable share. During the 2021-2023 energy crisis, nuclear-heavy countries showed stronger exposure. Results suggest that in integrated European markets, energy security depends on market design and infrastructure, not generation capacity alone.

[1]For this thesis, large language models (such as ChatGPT and Claude AI) were used only to improve language clarity and assist with coding for the empirical analysis. They were not used to generate original academic content or formulate arguments or conclusions. All intellectual contributions, interpretations, and scholarly insights presented in this thesis result from the authors' work.

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1. Introduction

Europe's energy system is defined by a tension between domestic resources, physical infrastructure, and market integration. Some countries benefit from abundant domestic resources, such as hydro in the Nordic region, nuclear power in France, offshore wind potential around the North Sea, or fossil fuel production in Norway and the United Kingdom. Others remain structurally dependent on imported energy. This uneven geography matters because energy security is not determined only by how much energy a country produces, but also by whether that energy can be transported, traded, consumed, and priced in ways that reduce exposure to external shocks.

This issue remains a central policy issue since the EU still depends heavily on imported energy (Sterling, Warusawitharana and Zhang, 2025). In 2023, the EU's energy import dependency rate stood at approximately 58.4 percent (Eurostat, 2023), meaning that more than half of the energy consumed in the bloc was met through net imports. This reliance exposes European countries to external supply disruptions, geopolitical risks, and international fossil fuel price volatility. The 2021-2023 energy crisis made this vulnerability particularly visible, as the reduction of Russian gas supplies and the surge in gas prices contributed to sharp increases in wholesale electricity prices across Europe (ACER, 2022).

The shift towards renewables in Europe is also seen as a solution to its vulnerability. Logically, expanding domestic renewable generation should reduce dependence on imported fossil fuels and improve resilience to external shocks. The problem is, however, that the connection between these processes is not straightforward. Indeed, energy is not perfectly movable: gas depends on pipelines, LNG terminals and storage, while electricity depends on grid capacity, cross-border interconnections and system flexibility. A country may therefore produce large quantities of low-carbon energy and still remain exposed if that energy cannot be absorbed domestically, exported efficiently, stored, or priced independently from fossil-fuel marginal technologies.

This matters particularly in Europe's wholesale electricity markets since they are generally organised based on marginal pricing, meaning the market-clearing price is set by the last and most expensive unit required to meet demand. ACER's assessment of the EU wholesale electricity market design highlights the role of gas plants in establishing the marginal electricity price in Europe (ACER, 2022). As a result, countries with substantial nuclear or renewable generation may remain exposed to gas price movements if gas remains the marginal technology in the wider interconnected system. This helps explain why the 2021-2023 crisis also affected electricity prices in countries with relatively low-carbon domestic generation mixes.

The policy relevance of this issue is reflected through the latest reform in electricity market design carried out by the EU. The reform, adopted in 2024, aims to make the European electricity market more resilient and to reduce the exposure of consumers and firms to short-term price volatility (Council of the European Union, 2024). This institutional response confirms that the link between fossil fuel prices, wholesale electricity markets, and energy security is not only an academic question, but also a central policy concern. The International Energy Agency also stresses that electricity grids need urgent investment and better planning to support secure energy transitions (International Energy Agency, 2023). This reinforces this paper's central idea: domestic generation matters if infrastructure allows energy to be moved, balanced and integrated across markets.

Existing research has examined parts of this problem separately. Studies on energy dependence show that renewable generation and energy efficiency can reduce import reliance and improve energy security (Carfora et al., 2022). Other work highlights the geographically uneven nature of the European energy transition, with countries progressing at different speeds depending on their initial resource endowments, industrial structures and policy choices (Piekut, 2024). Another part of the literature focuses on infrastructure constraints, showing that cross-border bottlenecks in gas and electricity markets can create price dispersion and regional vulnerability (Neumann, Rosellon and Weigt, 2015; Zachmann, 2008). Finally, the literature on wholesale electricity pricing and renewable integration explains why low-marginal-cost technologies can reduce average price levels without necessarily eliminating exposure to gas-set prices when market design and intermittency remain binding constraints (Sensfuß, Ragwitz and Genoese, 2008; Hirth, 2013).

The interaction between these mechanisms has not been tested as directly. Domestic resources are often discussed as a solution to import dependence, while interconnection and market integration are usually analysed through efficiency, congestion or price convergence. Yet in practice, these dimensions are inseparable. A country's domestic energy mix may matter less for energy security if its electricity prices are determined in an integrated market where gas-fired plants still set the marginal price. Conversely, a country with strong renewable potential may remain vulnerable if insufficient infrastructure prevents production from being absorbed domestically or traded efficiently.

This paper asks: How do domestic energy resources and transport constraints shape regional energy consumption and energy security in Europe? The analysis is organised around two connected empirical questions. First, we examine how domestic production structures translate into domestic consumption patterns across European countries. If domestic resources strongly determine consumption, countries that produce more fossil, nuclear or renewable energy should also consume more of that same energy family. Second, we test whether national energy mixes moderate the pass-through from gas prices to wholesale electricity prices. If low-carbon domestic generation protects countries from fossil fuel shocks, high-nuclear or high-renewable countries should display weaker sensitivity to gas price movements.

To answer these questions, the paper combines two panel datasets. The first is a long annual energy-balance panel covering 30 European countries from 2000 to 2023, built from Eurostat data. It is used to compare production and consumption structures across three energy families: fossil, nuclear and renewable. The second is a wholesale electricity price panel covering 2015 to 2024, using data from Ember Energy, Eurostat and the World Bank. This panel is used to estimate gas price pass-through and to test whether countries with higher nuclear or renewable shares respond differently to gas price shocks.

The findings challenge a simple view of domestic energy security. On the consumption side, domestic production matters, but only partially. Production shares translate into consumption shares with pass-through coefficients well below one, suggesting that trade, infrastructure and persistent country characteristics strongly mediate the relationship between what countries produce and what they consume. On the price side, gas prices are strongly and robustly associated with wholesale electricity prices across European countries. High renewable shares are associated with lower wholesale price levels once common time shocks are controlled for, but they do not significantly reduce sensitivity to gas price movements. During the 2021-2023 crisis, nuclear-heavy countries even display stronger, rather than weaker, gas price pass-through, although this effect appears crisis-specific rather than structural.

The contribution of this paper is to show that European energy security cannot be inferred from domestic generation capacity alone. The relevant question is not only what a country produces, but whether that energy can be consumed domestically, transported through interconnections, traded across borders, and priced independently from fossil-fuel marginal technologies. In an integrated European market, interconnection plays a dual role. In normal periods, it improves efficiency and allows low-cost electricity to move across borders. During periods of stress, however, the same integration can transmit gas-driven price shocks across countries, including to those with relatively low-carbon domestic generation mixes.

The rest of the paper proceeds as follows. Section 2 reviews the literature on domestic resources, transport constraints, wholesale electricity pricing and energy security. Section 3 presents the data, variables and empirical strategy. Section 4 reports the results for the production-to-consumption relationship and for gas price pass-through to wholesale electricity prices. Section 5 discusses the implications of the findings for European energy security and energy transition policy.

2. Literature Review

2.1 Domestic Resources and Electricity Generation

The European Union's energy transition landscape is characterised by a fundamental structural gap: while internal demand remains high, domestic production historically fails to keep pace, causing the EU to rely on imports for about half of its energy consumption (Carfora et al., 2022). As supply is often concentrated between a small number of players, this dependence represents a significant security risk, leaving member states more sensitive to price volatility and geopolitical shocks.

The starting point for most of the literature is that expanding domestic energy production, particularly through renewables, is the primary mechanism for reducing this vulnerability. Carfora et al. (2022) establish this relationship formally, arguing that renewable energy generation and energy efficiency are the main levers through which countries can lower import dependency and improve energy security. Their empirical analysis finds that expanding renewable capacity is closely correlated with reduced import demand across EU countries. However, a central limitation of their framework is that it assumes energy can reach its destination but it does not account for whether domestic production is actually deliverable to demand centers. This is particularly visible in the case of Spain, which has significant solar energy potential but suffers from chronically low interconnection capacity with the rest of Europe. As Carfora et al. (2022) note, this infrastructure gap can turn a country from a "leader" in production into a "laggard" in economic stability, because surplus domestic generation cannot be exported and therefore does not translate into system-wide security gains.

Piekut (2024) extends this analysis by examining the long-term dynamics of the energy transition across the EU-27 between 2004 and 2021. Using a clustering methodology based on energy efficiency, renewable share, and import reliance the paper identifies four distinct transition speeds: "gallop", "canter”, "trot" and "walk". The paper's central finding is that the transition is "geographically uneven": while the EU operates under common energy policy goals, national starting points differ dramatically due to the unequal geographic distribution of domestic resources. Our research builds on this observation by arguing that the "leader" or "laggard" status of a country is not solely a function of the resources it possesses, but also of its physical capacity to move those resources.

2.2 Transport Constraints and Market Integration

A technical reality of the energy transition is that energy cannot always be moved freely to where it is most needed. Gas depends on pipelines, LNG terminals, and storage; electricity requires grid capacity, reliable interconnections, and sufficient cross-border transmission. This restriction on "movability" results in a gap between what a country produces and what it can actually deliver.

Neumann, Rosellon and Weigt (2015) directly address this problem in the context of the European gas market. Their study documents how cross-border capacity bottlenecks generate price dispersion and regional vulnerabilities, showing that the gap between having a resource and being able to use it is not only technical but also financial and regulatory. Even when domestic gas or LNG is available, it may not reach end consumers if infrastructure rules make it more profitable for companies to maintain capacity constraints than to expand them. As for our research, this helps explain that domestic resources alone are not enough; countries also need the right transport mechanism to make sure resources actually improve energy security for the whole region.

The same phenomenon holds true in the electricity market. According to Zachmann (2008), European electricity wholesale markets have become progressively more interconnected since liberalisation, driven by growing cross-border interconnection capacity. This integration has improved efficiency and reduced average costs (Newbery, Strbac and Viehoff, 2016), but it has also created a channel through which price shocks originating in one market are transmitted across borders. The result is that countries well-connected to the European grid tend to receive a common price signal, partly independent of their domestic generation mix. Looking ahead, ENTSO-E's Ten-Year Network Development Plan (2024) identifies remaining infrastructure gaps and underlines that further grid expansion and flexibility investment are needed for renewables to contribute fully to energy security, reinforcing the point that physical infrastructure remains a binding constraint even as the low-carbon transition accelerates.

2.3 Wholesale Electricity Pricing and Gas Pass-Through

Understanding why domestic resources may not insulate countries from gas price shocks requires engaging with how electricity prices are actually formed. European wholesale electricity markets generally operate under marginal cost pricing: in each settlement period, the market-clearing price is set by the most expensive generating unit dispatched, often a gas-fired plant, especially during periods of tight supply or high demand. Under this mechanism, infra-marginal generators, including nuclear and renewable plants with lower operating costs, typically receive this market-clearing price. Increasing the share of renewables or nuclear power can reduce the volume of gas generation dispatched and put downward pressure on average prices, but may not eliminate gas price pass-through when gas-fired plants remain marginal in key periods (Sensfuß, Ragwitz and Genoese, 2008). European transmission interconnections then transmit this price signal across borders, meaning that market integration and domestic generation mix interact in determining how exposed any given country is to gas price movements.

This mechanism became central to the European energy policy debate during the 2021 to 2023 crisis. ACER's (2022) assessment of the EU wholesale electricity market found that the surge in gas prices following Russia's invasion of Ukraine contributed to unprecedented wholesale electricity prices across Europe, affecting countries regardless of their domestic generation mix. The episode directly motivated the European Commission's electricity market design reform, which entered into force in July 2024 and was explicitly aimed at reducing the link between short-term gas prices and consumer electricity bills (Council of the European Union, 2024) (Fabra, 2023; Pollitt et al.,2024). For our paper, this institutional context matters: it confirms that the gas-to-electricity price transmission we study empirically is not only a statistical regularity but a recognised structural feature of European market design.

2.4 Crisis Exposure and Uneven Protection Across Europe

The 2021 to 2023 energy crisis also underlined the non-uniformity of the protective value of domestic resources across countries or crisis conditions. Ang, Choong and Ng (2015), in a review of the energy security literature, identify three core dimensions that recur across most definitions: security of supply, economic efficiency, and environmental sustainability. The crisis simultaneously exposed tensions between supply disruption, price volatility, and pressure to accelerate the low-carbon transition; but it did so unevenly across Europe.

Countries with large nuclear fleets, such as France, did not necessarily experience lower wholesale electricity prices than more fossil-fuel-dependent economies, partly because integrated European markets transmitted the gas price shock across borders, and partly because the French nuclear fleet experienced significant availability problems in 2022 due to maintenance and corrosion issues (Gaulier and Serfaty, 2023). As Chalvatzis and Ioannidis (2017) observe in the context of island energy systems, the degree of isolation from wider networks is a double-edged sword: it can shield countries from imported price shocks, but it can also trap them in dependence on expensive local fossil fuels. A similar logic applies to continental energy "islands" : regions with abundant domestic resources but insufficient interconnection to trade those resources efficiently with neighbours during supply shocks.

2.5 Research Gap and Hypotheses

The existing literature has made significant progress in understanding each of these dimensions separately. We know that domestic renewables reduce import dependence on average (Carfora et al., 2022), that infrastructure bottlenecks generate price dispersion and regional vulnerability (Neumann, Rosellon and Weigt, 2015), that European electricity markets are becoming more integrated (Zachmann, 2008), and that marginal pricing can transmit gas price shocks even in countries with large low-carbon fleets (Sensfuß et al., 2008). We also know that the energy transition is proceeding at very different speeds across EU member states (Piekut, 2024), and that market design itself is recognised as a structural driver of this exposure (ACER, 2022).

What is less well understood is how these factors interact. There is limited empirical research on whether a country's domestic energy mix actually moderates its exposure to wholesale price shocks in an integrated European market, and especially under what conditions. Yet, these mechanisms are rarely tested together in the literature. A country with abundant low-carbon resources but strong grid interconnections may find that its domestic advantage is priced away through market integration. Conversely, a country with poor resources but weak interconnections may face a different kind of vulnerability through physical supply chain constraints instead of price transmission.

This paper aims to bridge this gap by testing whether energy mix composition reduces gas price pass-through to wholesale electricity prices across European countries, and by examining how this relationship changes under crisis conditions. Our central hypothesis is that even countries with strong low-carbon endowments may not be protected from gas price shocks if they are well-integrated into European wholesale markets. Energy security therefore depends on whether domestic production can be converted into actual consumption and price protection.

3. Data and methodology

3.1 Research design and data overview

The empirical analysis is organised around two connected questions. Question 1 asks how domestic production structures translate into domestic consumption patterns across European countries. Question 2 asks whether different national energy mixes are associated with different responses of wholesale electricity prices to gas price shocks. The two questions are answered with different data sources and panel structures, but they share the same underlying logic. In both cases, we test whether what a country produces domestically is enough to explain the outcome of interest, whether that outcome is a consumption volume or a wholesale price.

Energy security is a broad concept, and we do not attempt to capture all of its dimensions. Rather than treat it as a single index, we operationalise it through two measurable dimensions that the two questions address in turn. The first is physical security, reflected in the extent to which domestic production translates into domestic consumption and thereby reduces import dependence; this is the object of Question 1. The second is price security, reflected in the sensitivity of wholesale electricity prices to gas-price movements; this is the object of Question 2. Other dimensions of energy security, such as supply-disruption risk or long-run sustainability, lie outside the scope of these two measurable outcomes. Framing the analysis around physical security and price security keeps the contribution precise and makes explicit how the two empirical questions fit together.

For Question 1 we use a long annual panel covering 2000 to 2023, built from Eurostat's energy balances. For Question 2 we use a shorter annual panel covering 2015 to 2024, with a monthly extension over the same period, built from a combination of Ember Energy, Eurostat and World Bank data. The longer Q1 horizon is necessary to capture structural shifts in mixes and decoupling. The shorter Q2 horizon is dictated by the availability of consistent wholesale day-ahead prices across European countries.

3.2 Datasets and sample

The Question 1 panel is built from Eurostat's *nrg_bal_c* table (annual energy balances), accessed through the Eurostat Python package. After filtering, the working sample contains 250,560 country-product-year observations covering 30 countries (the EU-27 plus Norway, Switzerland and the United Kingdom) over 2000 to 2023. The five balance items kept are primary production (PPRD), imports (IMP), exports (EXP), gross inland consumption (GIC) and final energy consumption (FC_E). For the electricity sub-analysis we add gross electricity production (GEP), expressed in GWh. Switzerland is only partially covered for self-sufficiency, and the United Kingdom drops out of some Eurostat aggregates after Brexit. Both cases are flagged where they matter.

Eurostat encodes energy products through the *siec* dimension, which contains 72 codes ranging from very fine sub-products to broad aggregates. Working at the most disaggregated level is not informative for our research question, which is structural rather than technical. At the same time, using Eurostat's

TOTAL code introduces accounting biases because electricity and heat are counted both as primary inputs and as secondary outputs. We therefore reclassify each siec code into one of three energy families: fossil, nuclear and renewable. For every aggregated indicator we use a constructed total defined as the sum of the three aggregate Eurostat codes FE + N900H + RA000. This is more robust than the TOTAL aggregate and remains computable for countries where TOTAL is missing. The intermediate nine-label classification used to build the three families is described in Appendix A.

The Question 2 panel uses four datasets covering European countries from 2015 to 2024. The baseline annual panel has approximately 247 country-year observations across 27 countries. An extended monthly panel covers January 2015 to December 2024 and yields 2,919 country-month observations.

The dependent variable in all Question 2 specifications is the natural logarithm of the annual or monthly average wholesale day-ahead electricity price, expressed in EUR/MWh and sourced from Ember Energy. We use wholesale prices rather than retail tariffs because retail prices include taxes, network fees and policy levies that are mostly separate from spot market movements, which may weaken the gas price pass-through mechanism being examined.

The main explanatory variable in the baseline specifications is World Bank's natural-gas price series, measured in USD/MMBtu. The regressions use this variable in levels. In the annual specifications, it takes a single value per year common to all countries in the sample, so that it captures changes in the international gas-price environment faced by European countries without carrying cross-sectional variation. For the two-way fixed effects robustness specification, this index is replaced with country-level industrial gas prices from Eurostat (dataset nrg_pc_203, semi-annual, excl. taxes, industrial band), which vary across both countries and years. Pearson's pooled correlation between the series is r = 0.72.

Energy mix data for Question 2 are drawn from Eurostat's energy balance dataset (*nrg_bal_c*), expressed in GWh. Nuclear share and renewable share are computed for each country-year as the gross generation of each source category divided by total gross generation. For the monthly panel, these annual shares are held constant within each calendar year, which is a reasonable approximation because generation mixes change gradually relative to monthly electricity price fluctuations.

Table 1 summarises the main variables for both questions.

Table 1. Variable descriptions and sources

Variable	Source	Unit	Frequency	Role
Wholesale electricity price	Ember Energy	EUR/MWh	Annual / Monthly	Q2 dependent variable
World Bank natural-gas price series	World Bank commodity prices	USD/MMBtu	Annual / Monthly	Q2 main regressor (baseline)

Country-level gas price	Eurostat nrg_pc_203	EUR/kWh	Semi-annual	Q2 robustness regressor
Nuclear share	Eurostat nrg_bal_c	Share of gross generation	Annual	Q2 quartile dummies, interactions
Renewable share	Eurostat nrg_bal_c	Share of gross generation	Annual	Q2 quartile dummies, interactions
Primary production (PPRD)	Eurostat nrg_bal_c	ktoe	Annual	Q1 production volumes
Gross inland consumption (GIC)	Eurostat nrg_bal_c	ktoe	Annual	Q1 consumption volumes
Self-sufficiency ratio	Constructed from PPRD/GIC	Percent	Annual	Q1 control variable
Production/consumption mix shares	Constructed from nrg_bal_c	Share (0-1)	Annual	Q1 main variables
Bidirectional electricity trade	Eurostat min(IMP, EXP)	TWh	Annual	Q1 trade analysis

The Q2 panel is unbalanced because Bulgaria, Croatia, Ireland and Montenegro have missing wholesale price data in earlier years, thus fewer observations. All standard errors in Q2 are clustered at the country level (Wooldridge, 2002). All Q1 standard errors are heteroskedasticity-robust (HC3 for the panel regressions, HC1 for the trade regression).

3.3 Indicators and variables

For Question 1, three families of indicators are built from the cleaned panel. First, mix shares. For each country i and year t, the production-mix share of family f is the ratio of primary production for family f to the constructed production total. The consumption-mix share is defined the same way on gross inland consumption. Both quantities sum to 100 percent over the three families, which puts them in the simplex and has implications for the distance metric we use later. Second, the self-sufficiency ratio, defined following the Eurostat convention as primary production divided by gross inland consumption, expressed in percent. Values above 100 percent indicate a net energy exporter. Third, the electricity balance. For the electricity-specific block, gross electricity production replaces primary production, electricity is treated as the carrier (siec code E7000), and a net trade balance is computed as IMP minus EXP. Positive values flag net importers.

For Question 2, the variables are quartile dummies for nuclear share and renewable share, with the bottom quartile (Q1) as reference category. Quartile assignments are done cross-sectionally within each year, ranking countries by their annual generation share. The interaction terms between gas prices and top-quartile indicators (GasPrice × NuclQ4 and GasPrice × RenewQ4) are the main object of interest.

3.4 Empirical strategy for Question 1: production-to-consumption pass-through

We test at two levels how much of a country's production structure translates into its consumption.

Bivariate level. For each energy family we compute the Pearson correlation between production share and consumption share across the full panel ($n \approx 690$ country-year observations after dropping missing rows). This gives a first descriptive measure of the production-to-consumption link.

Multivariate level with country fixed effects. The bivariate test pools all heterogeneity into a single coefficient, which is unsatisfactory. A country with no nuclear capacity will mechanically show a zero on both axes for nuclear, which inflates the apparent correlation. We therefore estimate, separately for each family *f*:

$$share\_conso(i,t,f) = \alpha(i) + \beta(f) \cdot share\_prod(i,t,f) + \gamma(f) \cdot autonomy(i,t) + \varepsilon(i,t)$$

where $\alpha(i)$ is a country fixed effect that absorbs all time-invariant structural differences (geography, baseload technology, historical infrastructure choices), and autonomy(i,t) is the self-sufficiency ratio. Standard errors are heteroskedasticity-robust (HC3). The coefficient $\beta(f)$ is our object of interest. It measures the within-country pass-through from production share to consumption share, controlling for the country's overall import-export position.

We also run a complementary specification on **absolute volumes** (ktoe rather than shares), where $\beta(f)$ measures by how many ktoe consumption increases when production rises by one ktoe. A value of 1 means full domestic absorption. A value below 1 means part of the production is exported. A value above 1 means imports supplement domestic production.

Decoupling measures. A country can produce mostly renewable energy and still consume mostly fossil fuels if trade is active enough. The regression above cannot capture this because it works one family at a time. To quantify decoupling at the country-year level we compute the distance between a country's production-mix vector and its consumption-mix vector. Our baseline is a standard Euclidean distance. We also report the Aitchison distance, the geometry-respecting metric for compositional data, as a robustness measure (Aitchison, 1986). The technical details of both distances are reported in Appendix B. Each distance is then correlated with the self-sufficiency ratio to test whether high autonomy translates into low decoupling.

Clustering and transition speed. Two further descriptive steps are taken. First, we group countries into archetypes based on their 2022 production mix using a standard hierarchical clustering approach. The technical details (linkage method, standardisation, dendrogram cut, and the principal-component projection used for visualisation) are reported in Appendix B. Second, we estimate, country by country, the OLS slope of the fossil consumption share against the year over 2000 to 2023. Countries with fewer than 10 valid years are dropped. A negative slope indicates decarbonisation. A positive slope indicates re-carbonisation. We use the consumption share rather than the production share because consumption is what ultimately matters from a climate standpoint.

Cross-border electricity trade. Because mix decoupling is partly driven by trade, we close the Question 1 analysis with a regression of two-way electricity trade volume on renewable electricity production:

$$min(IMP, EXP)(i,t) = \alpha + \beta \cdot RA000(i,t) + \varepsilon(i,t)$$

with all variables in TWh. The dependent variable is the minimum of imports and exports, a measure of bidirectional trade intensity. It isolates genuine integration with neighbouring grids from net trade, which only reflects a country's overall surplus or deficit. Standard errors are HC1-robust. This specification directly tests whether countries that scale up renewables also scale up trade, as the literature on intermittency and cross-border balancing predicts.

3.5 Empirical strategy for Question 2: gas price pass-through

Four models are estimated using the annual Q2 panel. Each includes country fixed effects α(i), which control for time-invariant country-specific characteristics such as geography, persistent infrastructure differences, regulatory traditions, and stable features of national electricity systems.

Model 1 includes only the World Bank natural-gas price series as the main explanatory variable:

$$log(ElecPrice)it = \alpha i + \beta_1 \cdot GasPrice\ t + \varepsilon it$$

This provides a baseline estimate of the average gas price pass-through to wholesale electricity prices across all countries in the sample.

Model 2 adds quartile dummies for nuclear share and renewable share, with the bottom quartile (Q1) as the reference category. This tests whether countries with structurally different energy mixes are associated with systematically different wholesale price levels, independently of the gas price cycle:

$$log(ElecPrice)it = \alpha i + \beta_1 \cdot GasPrice\ t + \beta_2 \cdot NuclQuartile\ it + \beta_3 \cdot RenewQuartile\ it + \varepsilon it$$

Model 3 introduces interaction terms between World Bank's natural-gas price series and binary indicators for countries in the top quartile of nuclear share (nucl_q4) and renewable share (renew_q4). This specification directly tests the central hypothesis, which is whether high-nuclear or high-renewable countries respond differently to gas price shocks compared with other countries:

$$log(ElecPrice)it = \alpha i + \beta_1 \cdot GasPrice\ t + \beta_2 \cdot NuclQ4\ it + \beta_3 \cdot RenewQ4\ it$$
$$+ \beta_4 \cdot (GasPrice\ t \times NuclQ4\ it) + \beta_5 \cdot (GasPrice\ t \times RenewQ4\ it) + \varepsilon it$$

The coefficient β_4 captures whether countries in the top nuclear quartile exhibit a systematically different gas price pass-through coefficient relative to all other countries, and β_5 does the same for the top renewable quartile. A negative and significant β_4 would indicate that high-nuclear countries are partially insulated from gas price shocks at the wholesale level.

Model 3A extends Model 3 by including interaction terms for all quartile groups rather than the top quartile alone. This allows a test of whether the moderation of gas price sensitivity varies monotonically across the nuclear and renewable share distribution.

Fixed effects strategy. The baseline models include country fixed effects but not time fixed effects. This choice is imposed by the structure of the data. The World Bank gas-price series takes one value per year and is identical across all countries. Therefore, adding year fixed effects would absorb the same annual variation that the gas price variable is meant to capture, which would create near-perfect collinearity and make the gas price coefficient unidentified. This was verified empirically. When a two-way fixed effects specification was estimated using country-level Eurostat gas prices, which vary across both countries and years, the within-R^2 fell to -0.08, while the gas price coefficient turned negative and statistically insignificant. This indicates that year fixed effects capture most of the common annual variation in gas prices, leaving too little residual variation to reliably identify the pass-through effect.

In Model 3, however, the key variables of interest are not the standalone gas price index, but the interaction terms between World bank's natural-gas price series and the top-quartile indicators. Year fixed effects can therefore still be included in the interaction-based version of Model 3. These interaction terms continue to vary across countries within a given year, since countries differ in whether they are classified in the top nuclear or renewable quartile. This specification is reported as Model 3 TWFE and serves as an additional robustness check.

Robustness specifications. First, Model A replaces the global gas price index with country-level industrial gas prices from Eurostat. This allows both country and year fixed effects to be included. Second, Model B keeps the global gas price index but adds country-specific linear time trends. This absorbs slowly moving national trends without fully absorbing the common gas price variation. Third, the models are re-estimated excluding 2022. This checks whether the results are driven by the exceptional gas price spike during the European energy crisis. Fourth, Model 3 is re-estimated using continuous interactions between gas prices and nuclear and renewable shares, instead of top-quartile indicators, to test for sensitivity to the quartile classification. Finally, France is excluded from the sample and quartiles are recomputed. This is important because France dominates the top nuclear quartile, which means that the nuclear interaction results may partly reflect the specific French case rather than a broader cross-country pattern.

Monthly panel extension and bootstrap inference. The annual panel contains 247 observations, which limits statistical power, especially for detecting heterogeneous effects across countries. This issue is reinforced by the cluster structure of the data. With only 27 country clusters, cluster-robust inference may be unreliable. To address this, the analysis is extended to monthly frequency, producing 2,919 country-month observations. The monthly panel replicates the main annual specifications, including a TWFE version with country and year-month fixed effects alongside the interaction terms. To further address the small-cluster inference problem, a restricted wild cluster bootstrap is applied to the key interaction terms in the monthly Model 3, following the Rademacher weight approach with 999 replications and 27 country clusters (Cameron, Gelbach and Miller, 2008). Bootstrap p-values are reported alongside the standard cluster-robust p-values.

3.6 Identification assumptions and limitations

For Question 1, the key interpretive limitation is that the regressions are descriptive and correlational. Identification of causality is not straightforward since it would take a shock that impacts production but not consumption or a theoretical framework based on the structure of the European energy system. We therefore interpret our findings as stylised facts rather than causal evidence. The share-based aggregation also collapses each country's mix into three families. This is necessary for comparability across 30 countries and 24 years but hides important sub-family transitions such as the shift from coal to gas inside Fossil.

For Question 2, the main identification assumption is that, after controlling for country fixed effects, the World Bank natural-gas price series is uncorrelated with time-varying country-specific factors that also influence wholesale electricity prices. In practice, this assumption may be imperfect. Cold winters can raise both gas demand and electricity demand, and periods of low wind generation may push up electricity prices when gas prices are also elevated. Since the baseline specification does not include time fixed effects, the estimated gas price coefficient may partly reflect common European shocks rather than only fuel cost pass-through.

A second limitation concerns the interaction terms. Energy mix shares change slowly over time, especially for nuclear generation. After controlling for country fixed effects, there is limited within-country variation available to identify heterogeneous effects. The monthly panel increases the number of observations but does not create additional variation in energy mix shares, which remain annual.

A third concern is the potential endogeneity of the energy mix. Countries with large nuclear fleets may have invested in nuclear power partly to reduce exposure to fossil fuel price volatility. Nuclear share may therefore not be fully exogenous to the gas price sensitivity being estimated. The quartile approach partially reduces this concern by focusing on broad structural groups rather than exact continuous shares, but it cannot eliminate the issue.

Finally, the relatively small number of country clusters means that standard cluster-robust standard errors should be interpreted with caution. The wild cluster bootstrap results are treated as the preferred basis for inference on the interaction terms.

4. Results

4.1 Descriptive snapshot of European energy structures

Before turning to the two empirical questions, it is useful to look at the structural picture across European countries. The EU-27 self-sufficiency ratio stands at 42.5 percent in 2023, which means the bloc still produces less than half of what it consumes domestically. The cross-country dispersion behind this average is enormous. Norway was a structural net exporter throughout the period, with a self-sufficiency ratio above 600 percent from the early 2000s onward and a peak above 800 percent. Small island economies such as Malta, Cyprus and Luxembourg approach zero domestic production.

The 2022 production-mix snapshot shows three structural archetypes that the clustering analysis in Section 4.2.3 will formalise. A fossil-dominated periphery (Cyprus, the Netherlands, Ireland, Italy, the UK), a nuclear-anchored core (France above all, then Belgium, Slovakia, Czechia), and a renewable-leaning northern band (Sweden, Latvia, Portugal, Finland, Denmark, Austria). Importantly, the *consumption* mix tells a different story. When countries are sorted by fossil share in gross inland consumption, the ranking is much more compressed. Cyprus, Malta, Luxembourg, the Netherlands, Ireland and Italy all sit above 80 percent fossil consumption in 2022, and almost every country shows a fossil consumption share above 50 percent. The contrast between a relatively diverse production landscape and a relatively uniform consumption landscape is the first piece of direct evidence that domestic production structure does **not** mechanically determine consumption structure.

This first observation already motivates the rest of the empirical analysis. If consumption mixes are more uniform than production mixes, then trade, infrastructure and market integration appear to play an important role in determining what countries actually consume, and at what price.

4.2 Question 1 results: production-to-consumption pass-through

This section presents our empirical findings for Question 1: how do domestic resources and production structures influence consumption patterns and transition trajectories across European countries?

4.2.1 Pearson correlations by energy family

Across the full panel (n = 690 country-years), the Pearson correlations between production share and consumption share by energy family are sharply uneven:

Table 2. Pearson correlations: production share vs consumption share, by energy family

Author's calculation based on Eurostat nrg_bal_c.

Energy family	Pearson r	p-value	n
Fossil	0.371	6.8×10^{-24}	690
Nuclear	0.923	1.1×10^{-286}	690
Renewable	0.266	1.3×10^{-12}	690

All three correlations are highly significant, but their magnitudes differ by a factor of three to four. Nuclear shows what is essentially a deterministic relationship. A country either has nuclear and consumes it locally, or it has none and consumes none. This reflects the technical reality that nuclear electricity is overwhelmingly consumed in the country of generation. Cross-border trade of nuclear-origin electricity exists but is small relative to domestic baseload use. Renewables show the weakest pass-through, with r = 0.266. This is the most striking result. A country that produces mostly renewables does not, on average, consume mostly renewables. The fossil correlation falls in between, but closer to the renewable end.

When we run the same exercise on absolute volumes rather than shares, the picture changes dramatically: r climbs to 0.998 for renewables and to 1.000 for nuclear, against 0.370 for fossils. This is a useful sanity check but is largely due to large countries producing and consuming large amounts of every type of energy. The interesting cross-country variation is in shares, not in levels.

4.2.2 Within-country pass-through with fixed effects

The pooled correlations confound within-country and between-country variation. Estimating the fixed-effects model from Section 3.4 gives the following coefficients (heteroskedasticity-robust standard errors, full panel 2000 to 2023):

Table 3. Within-country pass-through with country fixed effects

Family	β (share_prod)	γ (autonomy)	R^2
Fossil	0.430***	-0.038*	0.942
Nuclear	0.433***	0.013***	0.989
Renewable	0.334***	0.014 (n.s.)	0.926

**** $p < 0.001$, * $p < 0.05$. HC3 robust standard errors. $n \approx 690$ country-year observations.*

The first important result is that the within-country pass-through is well below one in every energy family. A one-percentage-point increase in a country's renewable production share is associated with only 0.33 percentage points of additional renewable consumption share, holding self-sufficiency constant. The relationship is positive but incomplete because production structure alone does not determine consumption structure. Because the three family shares sum to one, these coefficients describe how changes in production composition map into changes in consumption composition rather than physical absorption rates. The complementary volume regressions below provide the more appropriate lens for interpreting domestic absorption.

In the renewable-share specification, fixed effects span a range of roughly 65 percentage points between the most renewable-leaning country (Norway, +31.4) and the least (Malta, -32.2). These coefficients represent the structural baseline consumption share that cannot be explained by current production. A country like Malta consumes far fewer renewables than its own production would predict, even after controlling for self-sufficiency, simply because of fixed structural factors such as small market size, no interconnection, no nuclear, and oil-based generation.

In absolute terms (ktoe specification), the pass-through coefficients are very different and informative in their own right: $\beta = 0.80$ for fossils, $\beta = 1.00$ for nuclear, and $\beta = 1.04$ for renewables. Nuclear's β of exactly 1.00 is mechanical and again reflects the near-perfect local absorption of nuclear output. The renewable coefficient slightly above 1 implies that an extra ktoe of domestic renewable production is associated with slightly more than an extra ktoe of renewable consumption, which is consistent with countries scaling up renewables also importing additional renewable energy at the margin. The fossil coefficient below 1 (0.80) is the mirror image of the share result. A marginal ktoe of fossil production is consistent with part of fossil production being exported or not translating fully into domestic fossil consumption.

4.2.3 Country archetypes

Hierarchical Ward clustering on the 2022 production-mix vectors yields six clean groups. The centroids on the three energy families are:

Table 4. Cluster centroids on the three energy families (2022)

Author's calculations based on Eurostat nrg_bal_c.

Cluster	Fossil	Nuclear	Renewable	Label
1	36.7 %	36.3 %	27.0 %	Balanced mix
2	4.3 %	66.3 %	29.4 %	Nuclear dominant
3	2.4 %	36.1 %	61.5 %	Renewables + nuclear
4	5.7 %	0.0 %	94.3 %	Renewable dominant
5	85.4 %	0.0 %	14.6 %	Fossil dominant
6	45.4 %	2.9 %	51.7 %	Fossil + renewables

The projection used for visualisation (Appendix B, Figure B2) explains 94.7 percent of the variation between countries in terms of their production mix, indicating that the six-cluster solution can be summarized in two dimensions. The clusters correlate very well with the description groups outlined in Section 4.1. The Fossil dominant cluster consists of the economies most prone to shocks. Renewables + nuclear and fossil + renewables clusters are transitional groups.

4.2.4 Mix decoupling and self-sufficiency

The mix-distance analysis quantifies how far each country's consumption mix sits from its production mix in a given year. The two metrics are strongly correlated (Pearson r = 0.900), so the metric choice matters for individual country rankings but not for the global picture. The detailed comparison and the sensitivity analysis are in Appendix B.

The LOWESS curve linking distance to self-sufficiency is decreasing and convex over the bulk of the sample. Countries with very low self-sufficiency (Malta, Cyprus, Luxembourg, Italy) show the largest mix gaps, while countries close to or above self-sufficiency (France, Sweden, Norway, Denmark) cluster around small distances. We rely on the LOWESS smoother rather than the pairwise Pearson correlation because missing values for Switzerland in the self-sufficiency series propagate through the correlation calculation and prevent us from reporting a clean numerical coefficient. The LOWESS smoother handles missing values pairwise and recovers the expected monotonic pattern, which is sufficient for the qualitative claim that decoupling and import dependence are tightly linked.

4.2.5 Speed of the transition and the 2022 shock

Country-by-country OLS slopes of the fossil consumption share over 2000 to 2023 reveal a continent that is decarbonising almost universally but at very unequal speeds. Of the 29 countries with sufficient data, 28 show a statistically significant negative slope. Only Lithuania shows a significant positive slope

(+1.2 pp per year, $R^2 = 0.5$), an outlier driven by the post-2009 closure of the Ignalina nuclear plant and the resulting substitution by gas-fired generation.

The top five decarbonisers measured by slope are Denmark (-1.6 pp/year, $R^2 = 1.0$), Finland (-1.0), Estonia (-0.9), Portugal (-0.8) and Czechia (-0.8). At the slow end of the (still decarbonising) distribution sit Belgium and Germany (both -0.2 pp/year). The slow German slope is consistent with one common interpretation of Germany as a slow transition case, in which the early phase-out of nuclear baseload before renewables could fully replace it may have slowed the fall of its fossil share.

The 2022 shock produced a clear yet uneven impact across countries. Between 2021 and 2022, fossil fuel consumption shares spiked in many places, largely because countries shifted toward coal as gas became too expensive. In 2023, this gap narrowed substantially and by then, most countries had moved back toward levels close to, or even below, their pre-shock trajectory. This recovery aligns with the wider post-2022 adjustment in energy dependency, driven by reduced demand and faster renewable energy deployment rather than a lasting return to fossil fuels (Eurostat, 2023).

4.2.6 Renewables and cross-border electricity trade

The electricity sub-analysis confirms that integration with neighbouring grids is increasingly important. At the EU-27 aggregate, electricity imports as a share of gross electricity generation rose from 9.6 percent in 2000 to 15.1 percent in 2022 (15.0 percent in 2023), and exports moved in parallel. Total cross-border electricity flows grew faster than generation itself. This is evidence of a continent that is more interconnected even as its overall power output stagnated post-2008.

The regression of two-way electricity trade volume on renewable electricity production confirms the predicted positive association:

$$min(IMP, EXP) = 0.004 + 0.107 \cdot RA000, \quad R^2 = 0.29, \quad n = 692$$

Both coefficients are significant at the 0.1 percent level under HC1 robust standard errors. We read this as a descriptive association rather than an identified effect. An additional TWh of renewable electricity production is associated with about 0.11 TWh of additional bidirectional trade, that is, both more imports and more exports. This is consistent with the view that intermittent renewables raise the option value of cross-border balancing.

The most trade-intensive economies relative to their own consumption are small and well-interconnected (Luxembourg, Denmark, Switzerland, Austria). The country-level import/export breakdown is provided in Appendix B, Figure B6.

4.3 Bridging paragraph: from volumes to prices

While Question 1 is looking at the broader energy balance, Question 2 focuses on electricity markets, where interconnection and marginal pricing are more directly observable.

The Question 1 results show that domestic production shapes consumption only partially. Production shares translate into consumption shares with coefficients well below one, and countries that scale up renewables also scale up cross-border electricity trade. Together these findings suggest that trade and interconnection mediate the link between national production and national consumption. Question 2 tests whether the same logic applies to prices. Even countries with low carbon domestic mixes may remain exposed to a European market where prices are shaped by cross-border flows and by the marginal technology that clears the system.

4.4 Question 2 results: gas price pass-through to wholesale electricity prices

This section presents our empirical findings for Question 2: do different energy mixes explain different responses of electricity prices to fossil fuel costs?

4.4.1 Baseline annual panel

The results are shown in Table 5. Across the three models, the coefficient on the gas price index is positive, highly statistically significant, and stable in magnitude, ranging from approximately 0.050 to 0.052. The associated t-statistics exceed 24 in all specifications. This suggests a strong positive relationship between international gas prices and wholesale electricity prices over the period studied.

Because the dependent variable is in logarithmic form, the coefficient can be interpreted semi-elastically. A one unit increase in the World Bank's natural-gas price series, measured in USD/MMBtu, is associated with approximately a 5 percent increase in wholesale electricity prices over 2015 to 2024. This result is stable across all three specifications and is the most precisely estimated coefficient in the analysis. It is consistent with the role of gas-fired power plants in setting the marginal clearing price in European electricity markets, especially during periods of high gas price volatility.

In Model 2, the renewable-share quartile dummies are positive and statistically significant. This indicates that countries in the second, third, and fourth renewable-share quartiles are associated with higher wholesale electricity prices relative to countries in the bottom renewable quartile, which is the reference group.

Table 5. Annual panel results (Models 1, 2, 3, 3A - quartile interactions, 4 - TWFE with country-level gas price).

Variable	Model 1	Model 2	Model 3	Model 3A	Model 4 - TWFE
gas_price	0.0517***	0.0503***	0.0501***	0.0547***	
	(41.39)	(35.57)	(24.05)	(12.36)	
gas_price_ctry					-1.351
					(-1.04)
nucl_q2		0.1221		0.1907	
		(0.77)		(1.00)	

nucl_q3		0.0665		0.1441	
		(0.32)		(0.58)	
nucl_q4		0.1707	0.0785*	0.2261	0.0712
		(0.84)	(1.82)	(0.96)	(0.67)
renew_q2		0.3094***		0.3566***	
		(5.90)		(5.91)	
renew_q3		0.4823***		0.5311***	
		(9.91)		(9.80)	
renew_q4		0.5560***	0.0792	0.5794***	-0.1745***
		(6.89)	(1.37)	(8.48)	(-2.90)
gas × nucl_q4			0.0034	-0.0003	
			(1.01)	(-0.06)	
gas × renew_q4			0.0024	0.0011	
			(0.81)	(0.24)	
gas × nucl_q4_ctry					0.173
					(0.11)
gas × renew_q4_ctry					0.945
					(0.70)
N	247	247	247	247	231
R^2 (within)	0.823	0.851	0.825	0.855	-0.080
Country FE	Yes	Yes	Yes	Yes	Yes
Time FE	No	No	No	No	Yes

*t-statistics in parentheses. Standard errors clustered by country. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Models 1 to 3A use the World Bank natural-gas price series. Model 4 uses Eurostat country-level industrial gas prices (EUR/kWh, excl. tax) and includes both country and time fixed effects. Model 4 coefficient on gas_price_ctry is on a different scale and is not directly comparable to Models 1 to 3A. The negative within-R^2 in Model 4 reflects the limited residual variation in the country-level gas price once both fixed-effect dimensions are absorbed. Source: Author's calculations on Ember, World Bank Commodity price data, Eurostat (nrg_bal_c, nrg_pc_203)*

4.4.2 Two-way fixed effects specification

Adding time fixed effects to Model 3 required within-year variation in the gas regressor that the annual global index does not provide; thus we estimate this two-way fixed effect on the monthly panel. We called this specification Model 3 TWFE and reported it in Table 6. The standalone World Bank natural-gas price series is dropped, but the level dummies and the two interaction terms are kept. The interaction terms remain insignificant. The level dummy renew_q4 turns negative and significant.

Once year fixed effects are introduced, the coefficient on the high-renewable indicator changes sign. This suggests that the earlier positive association could have been partly driven by common annual shocks. In particular, the years with the highest gas prices also corresponded to periods of sharply higher wholesale electricity prices, which means that even countries with large renewable shares were affected by the broader European energy crisis. What is important here is that once the effect of annual shocks is taken away, we observe a residual negative association between renewable shares and electricity prices. It means that once we control for annual shocks, countries with large shares of renewables tend to have lower wholesale electricity price levels. One way to interpret this structural effect is that the marginal costs of producing renewable energy are lower compared to gas-powered electricity.

At the same time, the effect observed above does not carry over to the interaction terms in Model 3 TWFE, which remain statistically insignificant. It means that countries with a high level of renewables in their energy production mix do not have systematic differences from other countries in reacting to gas price changes. Although the price levels may differ depending on the renewable share, the price sensitivity to gas price variations remains unchanged.

4.4.3 Monthly panel extension

The results are reported in Table 6. The gas price coefficient remains positive and highly significant in Models 1 to 3. The within-R^2 values range from 0.509 to 0.541 across the three specifications, indicating reasonable within-country fit. In contrast, the within-R^2 in the TWFE specification falls to 0.027. After both country and year-month fixed effects are removed through double demeaning, the World Bank natural-gas price series becomes perfectly collinear with the month dummies and so is dropped from the model. The remaining regressors are the level dummies for nucl_q4 and renew_q4 and their interactions with the gas index, which still vary across countries within a given month. The low within-R^2 likely reflects the fact that these four regressors alone explain only a small share of the residual variation in wholesale prices. The model is not failing, it shows what the data has left to say once both fixed-effects dimensions are absorbed.

Two findings stand out in the TWFE specification. First, the level dummy renew_q4 turns strongly negative and significant. Once common annual and monthly shocks are absorbed, countries in the highest renewable quartile have systematically lower wholesale price levels. This mirrors the annual result we report in Section 4.4.2. Second, both interaction terms remain insignificant with small but positive coefficients. The magnitudes are small enough for the interaction story to say that the energy mix does not meaningfully insulate wholesale prices from gas movements at this frequency, and any sensitivity it does add is small.

In Model 3, gas×nucl_q4 is estimated at 0.0041 with a t-statistic of 2.28 ($p = 0.023$). A wild cluster bootstrap correction ($B = 999$, $G = 27$) yields a bootstrap p-value of 0.045, so the result holds at the 5 percent level under both inference approaches. The gas×renew_q4 interaction remains insignificant (t

= 0.19). The sign of the nuclear interaction is positive, which suggests that countries in the top quartile of nuclear generation shares display stronger pass-through from gas prices to wholesale electricity prices, not weaker. We return to this finding in Section 4.4.4.

Table 6. Monthly panel results (Models 1, 2, 3, 3 with TWFE).

Variable	Model 1	Model 2	Model 3	Model 3 TWFE
gas_index	0.0457***	0.0444***	0.0446***	dropped
	(41.24)	(33.46)	(26.94)	
nucl_q4		0.3012	0.1961***	0.0313
		(1.58)	(3.87)	(0.27)
renew_q4		0.6037***	0.1199	-0.1880***
		(4.22)	(1.12)	-2.92
gas × nucl_q4			0.0041**	0.0020
			(2.28) p_boot = 0.045	(0.92)
gas × renew_q4			0.0005	0.0020
			(0.19) p_boot = 0.836	(0.85)
N	2,919	2,919	2,919	2,919
Country clusters	27	27	27	27
R^2 (within)	0.509	0.541	0.515	0.027
Country FE	Yes	Yes	Yes	Yes
Time FE	No	No	No	Yes

*t-statistics in parentheses. Standard errors clustered by country. Bootstrap p-values (p_boot) from restricted wild cluster bootstrap (B = 999, Rademacher weights, G = 27 country clusters). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Monthly nuclear and renewable shares are held constant within each calendar year. Model 3 TWFE drops the World Bank natural gas price series because it is collinear with the year-month fixed effects (one global value per month, common to all countries). The interaction terms remain identifiable because they vary cross-sectionally within each month. Source: Author's calculations based on Ember, World Bank Commodity price data and Eurostat nrg_bal_c.*

4.4.4 Robustness checks

We ran three robustness tests on Model 3 with the monthly Model 3 specification with country fixed effects, focused on the interaction term gas×nucl_q4. The results are shown in Table 7.

2022 exclusion. The nuclear interaction weakens and becomes statistically insignificant ($t = 1.32$). This suggests that the result is not only driven by 2022 but becomes weaker when that year is removed.

Crisis window exclusion (September 2021 to June 2023). The nuclear interaction disappears this time, with t negative around -0.02. This confirms that the estimated effect is concentrated in the crisis period and is essentially undetectable outside it.

Lagged version. The question here is whether last month's gas price predicts this month's electricity price better than, or differently from, this month's gas price. The t-statistic moves only slightly (2.28 in the baseline, 1.97 with the lag). Switching to the lagged gas price does not meaningfully change the result. This is informative because if transmission were delayed, the lagged gas price would be a stronger predictor than the contemporaneous one. We would see the lagged version give a higher t-statistic and the contemporaneous version give a weaker one. The fact that the lagged specification gives an almost identical result suggests that gas price shocks transmit to wholesale electricity prices quickly enough to be captured within the same monthly observation.

The three robustness checks are consistent in showing that the nuclear interaction remains positive but is already statistically insignificant when 2022 is excluded and collapses when the entire crisis window is removed. Outside that window, the effect is essentially zero. This points to crisis dynamics rather than any permanent structural difference in high-nuclear electricity markets.

A fourth robustness check excludes France from the annual panel sample, the dominant Q4 nuclear country. During 2022, France experienced extraordinary supply-side disruptions due to stress-corrosion cracking affecting approximately half of its reactor fleet. The annual panel is used here because the gas×nucl_q4 interaction term is defined at that frequency. The monthly equivalent is assessed via the rolling β overlay in Appendix C. The France exclusion (N = 237, after dropping France's 10 country-year observations) shows the gas×nucl_q4 coefficient is stable in magnitude and remains insignificant, consistent with the full-sample result. The monthly rolling estimates are virtually identical with and without France (median β: 0.039 vs 0.038). Excluding France does not materially alter the annual interaction estimate, while the rolling analysis shows that France also does not drive the broader aggregate gas-price relationship. The nuclear interaction result should be interpreted not as a France artefact, but as a genuinely weak and imprecisely estimated effect across the full panel.

Table 7. Robustness checks for gas×nucl_q4 across subsamples and specifications.

Variable	Baseline	Excl. 2022	Excl. crisis	Lag gas (t-1)
gas price (USD/MMBtu)	0.0446***	0.0368***	0.0321***	0.0473***
	(26.94)	(29.25)	(18.28)	(28.82)
nucl_q4	0.1961***	0.2202***	0.2177***	0.1914***
	(3.87)	(3.35)	(3.07)	(3.64)
renew_q4	0.1199	0.1185	0.0706	0.0938
	(1.12)	(1.32)	(0.73)	(0.93)

gas × nucl_q4	0.0041**	0.0027	-0.0002	0.0040**
	(2.28)	(1.32)	(-0.05)	(1.97)
gas × renew_q4	0.0005	0.0003	0.0001	0.0010
	(0.19)	(0.13)	(0.03)	(0.37)
N	2,919	2,619	2,364	2,892
Country clusters	27	27	27	27

*t-statistics in parentheses. Standard errors clustered by country. * p < 0.10, ** p < 0.05, *** p < 0.01. Crisis window: September 2021 to June 2023. Lag specification uses gas_index_lag1, the global gas price index shifted by one month within country. All specifications include country fixed effects.Sources: Author's calculations based on Ember, World bank Commodity price data and Eurostat nrg_bal_c.*

4.4.5 Synthesis of Question 2 findings

First, gas prices are strongly and robustly associated with wholesale electricity prices across European countries. This result is very stable across specifications, sample choices and frequencies. In the annual panel, the coefficient on gas prices is always strongly significant, with t-statistics above 20, and the same positive relationship is found in the monthly panel.

Second, the results do not show clear evidence that, under normal market conditions, a country's energy mix reduces the pass-through of gas prices to wholesale electricity prices. In the baseline annual models, both interaction terms gas×nucl_q4 and gas×renew_q4 are statistically insignificant. The same conclusion is also obtained in model 3 TWFE. Countries with high nuclear or renewable shares do not seem to react systematically differently to gas price movements.

Third, countries with high renewable shares may have lower wholesale electricity price levels, but not lower sensitivity to gas price changes. In the monthly Model 3 TWFE, the renew_q4 dummy becomes negative and significant (-0.188, t = -2.92). Once common annual shocks are controlled for, countries in the highest renewable quartile tend to have lower wholesale electricity price levels. However, this effect is not observed for the interaction term. The gas×renew_q4 interaction is statistically insignificant in the baseline annual and monthly specifications. In the monthly TWFE specification, it stays small, positive and insignificant. This does not indicate insulation from gas-price movements. A hypothesis is that the sign points to a slightly stronger sensitivity, although the estimated magnitude is economically very small.

Fourth, the nuclear interaction gives a different result during the 2021 to 2023 energy crisis. In this period, the estimated interaction is positive, meaning that countries with the highest nuclear shares actually show stronger, not weaker, pass-through from gas prices to wholesale electricity prices. The result remains significant after applying the wild cluster bootstrap correction (p = 0.045, B = 999), but it is concentrated in the crisis period and disappears when the crisis years are removed.

Taken together, Question 2 results yield a consistent pattern across annual and monthly panels, two-way fixed effects specifications, and multiple robustness checks. Gas prices are the most robust driver of wholesale electricity price variation in Europe, and a country's energy mix does not significantly attenuate this transmission at the wholesale level under standard market conditions.

5. Discussion

5.1 Domestic production is not the same as domestic consumption

As opposed to a strong-form interpretation of the narrative of "domestic production drives domestic consumption", the results in Question 1 support a weak-form interpretation. A strong form one would predict pass-through coefficients close to one. What we find instead is a pass-through ranging between 0.33 and 0.43 depending on the energy family, and fixed effects spanning more than 60 percentage points for the renewable energy family. Producing one extra unit of a given energy family does shift a country's consumption mix in the same direction, but only by about one third of the move. Structural factors, such as geography, infrastructure and market design, play an equally important role here.

Nuclear serves as the limiting case of near-perfect domestic absorption, which is confirmed by near-deterministic correlation ($r = 0.92$, β-absolute = 1.00). Nuclear output is electricity, that electricity is overwhelmingly consumed within the producing country's grid, and the technology is concentrated in a handful of producers. Yet the fact that nuclear fixed-effects regression still yields β of only 0.43 speaks precisely to the distinction between volume and shares. The latter measures substitution within the mix, while the former captures a physical conservation law. The fact that the two tell different stories is in itself a meaningful result, not a flaw.

The decoupling analysis adds a further layer by showing how the production mix lever can be partially weakened by the interdependence of the European energy systems. While producing more renewables increases a country's self-sufficiency, a country with high renewable self-sufficiency still requires external supplies of fossils, which explains the monotonically-decreasing curve in the Aitchison distance LOWESS plot. Among the three production families, only renewables and nuclear are almost completely domestic in nature. By contrast, fossil production is substantially exported, and fossil consumption is met by fossil imports from Norway and the UK. This cross-border pattern is a function of the geographical positioning of the fossil producers within the European energy system.

These results are consistent with the broader literature on the *Renewable-Security Paradox*. Carfora et al. (2022) argue that scaling up domestic renewables should mechanically reduce import dependence. Neumann et al. (2015) counter that without simultaneous investment in transport infrastructure, this scaling-up creates "energy islands" with high curtailment risk and unchanged consumption profiles. Our results are consistent with the Neumann mechanism. The production-mix lever exists, but its bite is dampened by the very infrastructure constraints they emphasise. Spain, with high domestic renewable potential and low interconnection capacity, is exactly the kind of country that the fixed-effects analysis picks up as having a sizeable negative effect on the renewable consumption share relative to its production.

5.2 Low-carbon production is not the same as price insulation

Question 2 extends the same logic to prices. The results show that gas prices remain the dominant driver of wholesale electricity prices across European countries, and that a country's energy mix does not significantly reduce this pass-through under normal market conditions. The interaction terms gas×nucl_q4 and gas×renew_q4 are statistically insignificant in the baseline annual models, in the Model 3 TWFE extension, and in the monthly Model 3 outside the crisis window. Even countries with very low-carbon domestic mixes, such as France or Sweden, are not systematically insulated from gas price movements at the wholesale level.

This conclusion comes with a limitation: once common annual shocks are absorbed by year fixed effects, countries in the highest renewable quartile do show lower wholesale price levels (the renew_q4 dummy becomes negative and significant). This means that the renewable share is associated with structurally lower wholesale prices, even though it is not associated with lower price sensitivity to gas movements. The distinction between price levels and price sensitivity matters and is preserved throughout our interpretation.

5.3 Why both results point to marginal pricing and interconnection mechanisms

This result may seem counter-intuitive given that renewable technologies generally have low marginal generation costs. It is not inconsistent, however, with marginal pricing in European electricity markets. When gas-fired plants are needed to balance demand, they can set the clearing price for the wider interconnected market (Gasparella, Koolen and Zucker, 2023). In that case, a country’s domestic generation mix does not necessarily protect it from a price set elsewhere in the system. This does not mean that renewables cause higher electricity prices but rather that higher renewable penetration did not automatically translate into lower gas-price sensitivity during the studied period of our paper. The result may also reflect integration costs and the capital-intensive nature of renewable investment, especially when variable generation requires additional flexibility, storage and grid reinforcement (Hirth, Ueckerdt and Edenhofer, 2015).

The two halves of the empirical analysis converge on the same underlying mechanism. On the volume side, cross-border electricity trade is the channel through which production-mix differences fail to translate fully into consumption-mix differences. Countries that scale up renewables also scale up bidirectional trade, by about 0.11 TWh of additional two-way trade per additional TWh of renewable generation. On the price side, the same interconnections that allow renewable surpluses to be exported also transmit gas-set marginal prices back across borders. Interconnection therefore plays a dual role. In normal periods it allows cheaper electricity to move across borders and helps lower-cost technologies, such as hydro or nuclear power, reach higher-price markets. During periods of stress, it also transmits gas-set marginal prices across the European grid.

5.4 The 2022 shock as a stress test

The 2022 energy shock provides a natural stress test of this mechanism. On the volume side, the fact that the 2021 to 2023 fossil-share differential is much smaller than the 2021 to 2022 differential, and negative for many countries, suggests that the shock did not derail the transition. The short run evidence is consistent with demand destruction and faster renewable deployment after the shock. On the price side, the gas-electricity link became unusually visible because gas prices reached record highs and wholesale electricity prices rose accordingly. Our crisis-window robustness check shows that the nuclear interaction term, which is essentially zero outside the crisis, becomes positive and significant during 2021 to 2023.

This crisis-period result should be interpreted carefully. The natural first hypothesis is the specific situation of France during the crisis. Stress-corrosion problems made a large part of the French nuclear fleet unavailable in 2022. At the peak of the disruption, around half of the fleet was offline, and France became a net electricity importer for the first time in several decades, which made it more exposed to gas-set import prices than usual (Gaulier and Serfaty, 2023). However, the France-exclusion robustness check in Section 4.4.4 shows that the coefficient on gas×nucl_q4 is stable in magnitude when France is dropped from the sample. French outages alone do not drive the result.

The most consistent reading of the two findings is that the positive nuclear interaction reflects a broader European crisis dynamic rather than a country-specific shock. During 2021 to 2023, wholesale prices rose together across the continent and the marginal-pricing channel transmitted gas-set prices uniformly, including to nuclear-heavy countries that would normally be less exposed. The nuclear coefficient becomes mildly significant in this window not because nuclear systems became more exposed to gas as a structural feature, but because the entire European wholesale market was operating under stressed conditions in which interconnection was amplifying rather than buffering price transmission. Outside the crisis window the effect disappears, which is consistent with this market-stress interpretation. We therefore treat the result as crisis-conditional and do not generalise it to a structural property of nuclear-heavy electricity markets.

5.5 Implications for European energy transition policy

First, domestic resources matter but they are not enough. A country's production mix does not mechanically determine its consumption mix. Trade, interconnection and infrastructure shape what countries actually consume, and they shape it strongly enough to absorb roughly two thirds of any change in production share. Energy security policies that focus exclusively on building domestic generation, without addressing transport and storage, are likely to over-estimate the security gains from new investment.

Second, a low-carbon content of generation fails to shield domestic prices from gas shocks. There is no insulation in place at the wholesale spot market, and any shielding mechanism would likely take place via retail-regulated or national policy means.

Third, the same interconnection infrastructure that supports the energy transition also transmits stress. In normal periods, interconnections improve allocative efficiency and reduce price dispersion. During crises, they transmit gas-set marginal prices uniformly across the continent. The protective value of domestic low-carbon resources therefore depends on the design of the market layer, not only on the physical generation mix.

This suggests European energy policies should not evaluate energy security only through installed renewable or nuclear capacity, but also through storage, interconnection capacity, grid flexibility, market design and finally the degree of exposure to marginal fossil-fuel price setting.

5.6 Limitations

The first limitation for Question 1 is that our analysis relies on a simplified three-family classification of energy sources: fossil, nuclear and renewable. This aggregation improves comparability across 30 countries and 24 years, but hides important within-category transitions, such as the shift from coal to gas inside the fossil category. We also use a constructed total based on FE + N900H + RA000 rather than Eurostat's TOTAL aggregate, meaning that the resulting shares should be interpreted as shares of primary energy within these three families rather than of the entire energy system.

A further framing limitation concerns transport constraints. Although they are central to the paper's argument, they are not measured directly through variables such as interconnection capacity, pipeline capacity, LNG infrastructure, congestion or storage availability. The main empirical proxy is the relationship between renewable electricity production and two-way electricity trade, which speaks to market integration rather than to physical transport capacity as such. We therefore treat interconnection and transport constraints as a mechanism supported by descriptive evidence and consistent with the literature, rather than as a directly identified causal variable. Introducing an explicit transmission-capacity indicator and testing whether it moderates the relationships studied is left for future work.

A further limitation for the decoupling analysis is that the relationship between mix-distance and self-sufficiency is interpreted descriptively. Incomplete self-sufficiency coverage for Switzerland prevents us from relying on a fully comparable headline correlation coefficient across the whole sample. We therefore use the LOWESS pattern as supporting evidence rather than as a formal statistical test.

Finally, the Question 1 results should be interpreted as descriptive rather than causal. The production-to-consumption regressions identify strong associations between domestic production, self-sufficiency and consumption patterns, but they do not prove that changes in domestic production cause changes in consumption. A causal interpretation would require either a valid production shock or a structural model of the European energy system.

For Question 2, the results are affected by the structure of the price data and the gas price variable. Because the global gas price index takes the same value for all countries in a given year, the baseline specification cannot include year fixed effects without absorbing the main variable of interest. As a result, the gas coefficient may partly capture common European shocks rather than pure fuel-cost pass-through. In addition, because the number of country clusters is limited, which makes standard cluster-robust inference less reliable, the wild cluster bootstrap is the preferred basis for inference on the interaction terms. Finally, energy mix shares change slowly over time, especially for nuclear generation, which limits the within-country variation available to identify heterogeneous pass-through effects.

5.7 Closing remarks

Taken together, the two empirical questions point to the conclusion that European energy security cannot be read simply from domestic generation capacity alone. The connection between the two findings is the integration of the European energy system itself: cross-border electricity trade, interconnection capacity, and the marginal-pricing rule of European wholesale markets. The energy transition is not only about what each country generates at home. It is also about whether energy can be consumed domestically, traded across borders, moved through interconnections, and priced within integrated electricity markets. A country's resilience and eventual position in a decarbonised European system depend on all these structural attributes, rather than a single one.

6. Conclusion

This paper examined how domestic energy resources and transport constraints shape energy consumption and energy security across Europe. The central question was whether domestic production genuinely protects countries from fossil fuel exposure, or whether this protection is weakened by trade, infrastructure constraints and wholesale electricity market design.

The first part of the analysis shows that domestic production matters, but only partially. Pass-through coefficients from production shares to consumption shares show that countries producing more of a given energy type do not necessarily consume that same energy in proportion. The result is especially notable for renewables, where the production to consumption link is weakest. Trade, infrastructure and persistent country characteristics therefore have a role in shaping what countries actually consume, independently of what they produce.

The second part of the analysis shows that low-carbon generation is not the same as price insulation. Gas prices remain the dominant driver of wholesale electricity prices across European countries. Countries with higher renewable shares tend to have lower wholesale price levels, but do not show systematically weaker sensitivity to gas price movements. High nuclear shares also offer no clear insulation in the baseline models. During the 2021 to 2023 energy crisis, nuclear-heavy countries display stronger gas price pass-through, a finding that appears crisis-specific rather than structural, but reinforces the point that domestic generation capacity does not guarantee price protection.

These results challenge a view of energy security built on installed capacity alone. Domestic resources are important, but their protective value depends on whether energy can be absorbed domestically, traded across borders and priced independently from fossil-fuel marginal technologies. Interconnection plays a dual role in this system. In normal periods, it supports efficiency and cross-border balancing. In periods of stress, it transmits gas-driven price shocks across markets, including to countries with relatively low-carbon generation mixes.

The policy implication is direct. European energy security cannot be evaluated through renewable or nuclear capacity alone. It also depends on storage, grid flexibility, interconnection and the exposure of wholesale prices to marginal fossil-fuel generation. Building domestic capacity without addressing these mechanisms risks overstating the security gains of the energy transition.

The analysis has limitations. The production-consumption regressions are descriptive rather than causal, and the use of a global gas price index restricts the use of time fixed effects in the baseline specification. Nonetheless, the findings are consistent across both empirical questions: energy security in Europe is a system-level outcome, shaped not only by what countries produce, but by how energy moves, how markets clear, and how shocks spread across an integrated system.

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Appendix A. Energy Product Classification

Eurostat encodes energy products through the siec dimension, which contains 72 codes ranging from very fine sub-products to broad aggregates. Working at the most disaggregated level is not informative for a structural research question, while Eurostat's TOTAL aggregate introduces accounting biases because electricity and heat are counted both as primary inputs and as secondary outputs. We map each siec code through an intermediate nine-label classification into one of three broad energy families: fossil, nuclear and renewable. This appendix documents that mapping.

The classification proceeds in two steps. First, each raw siec code is assigned a granular label on the basis of its leading character (Table A1). Second, each granular label is collapsed into one of the three broad families, with electricity and heat carriers and any residual codes routed to a non-family "Other" category that is excluded from the family shares (Table A2).

A1. Granular classification rule

siec code (leading character)	Description	Granular label
TOTAL	Eurostat all-products aggregate (not used as denominator)	TOTAL
FE	Fossil-energy aggregate (a family input to the constructed total)	Fossil aggregate
N900H	Nuclear heat	Nuclear
C…	Solid fossil fuels	Coal
G…	Gases	Natural gas
O…, S…	Oil and petroleum products	Oil
P…	Peat and peat products	Peat
R…, BIOE	Renewables and biofuels	Renewables
W…	Non-renewable waste	Non-renewable waste
E…, H…	Electricity and heat carriers	Electricity/Heat
Any other code	Unclassified residual	Other

Table A1. *Assignment of raw Eurostat siec codes to the granular labels, based on the leading character of the code. The all-products aggregate TOTAL is not used as the denominator; the fossil-energy aggregate FE is one of the three family inputs to the constructed total (see Table A3).*
Source: Eurostat nrg_bal_c siec dimension; authors' classification.

Non-renewable waste is grouped with the fossil family. This reflects its non-renewable combustible nature and keeps the simplified three-family framework exhaustive; the volumes involved are small relative to coal, oil and gas, so the choice does not materially affect the family shares.

A2. Mapping of granular labels to the three families

Granular label	Broad family
Coal	**Fossil**
Natural gas	**Fossil**
Oil	**Fossil**
Peat	**Fossil**
Non-renewable waste	**Fossil**
Nuclear	**Nuclear**
Renewables	**Renewable**
Electricity/Heat	Other (excluded)
Other	Other (excluded)

Table A2. *Collapse of the nine granular labels into the three broad energy families. Electricity and heat carriers are routed to a non-family "Other" category to avoid double-counting secondary energy, and are excluded from the family shares. Source: Eurostat nrg_bal_c; authors' classification.*

A3. Aggregate codes used for the constructed total

For every aggregated indicator (primary production, gross inland consumption and gross electricity generation), the family volumes are taken directly from the three Eurostat aggregate codes listed in Table A3, and the denominator is their sum. This constructed total (FE + N900H + RA000) is more robust than Eurostat's TOTAL aggregate and remains computable for countries where TOTAL is missing, such as the United Kingdom after Brexit and, partially, Switzerland.

Eurostat code	Description	Family
FE	Fossil energy aggregate	Fossil
N900H	Nuclear heat aggregate	Nuclear
RA000	Renewables and biofuels aggregate	Renewable

Table A3. *Aggregate Eurostat codes used to build the family volumes and the constructed total. The denominator for all family shares is FE + N900H + RA000. Source: Eurostat nrg_bal_c; authors' construction.*

The resulting shares should therefore be read as shares of primary energy within these three families rather than of the entire energy system. For the electricity sub-analysis, the same three aggregate codes are applied to gross electricity generation (GEP, in GWh), and electricity is treated as the carrier (siec code E7000) when computing the cross-border trade balance.

Appendix B. Q1 Methodological Details and Supporting Figures

This appendix documents the technical details of the distance metrics and clustering procedure used in Section 4.2, and then collects the supporting figures. Section B.1 provides the methodological note promised in Section 3.4; Section B.2 reproduces the three figures referenced in the main text (Figures 4.1 to 4.3); Section B.3 presents the additional figures B1 to B6. All figures use Eurostat nrg_bal_c and the authors' own calculations.

B.1 Distance metrics and clustering procedure

Mix vectors. For each country i and year t, the production-mix vector p_{it} and the consumption-mix vector c_{it} collect the three family shares (Fossil, Nuclear, Renewable), each summing to one. The decoupling between what a country produces and what it consumes is measured as the distance between these two vectors.

Euclidean distance. The baseline metric is the standard Euclidean distance, $d\_E = \sqrt{\Sigma_k (p_k - c_k)^2}$, summed over the three families k. It is simple and directly interpretable in percentage-point units, but it ignores the compositional (simplex) nature of the shares.

Aitchison distance. As a geometry-respecting robustness measure for compositional data, we also compute the Aitchison distance, defined as the Euclidean distance between the centred log-ratio (clr) transforms of the two mix vectors: $d\_A = \sqrt{\Sigma_k (\mathrm{clr}(p)_k - \mathrm{clr}(c)_k)^2}$, where $\mathrm{clr}(x)_k = \ln(x_k) - \mathrm{mean}_j \ln(x_j)$. Because the clr transform is undefined for zero shares, zeros are first handled by multiplicative replacement: each zero is set to a small pseudo-count ε and the non-zero shares are reduced proportionally so that the vector continues to sum to one. The baseline uses ε = 0.5 percentage points.

Sensitivity analysis. Because the pseudo-count is an arbitrary modelling choice, Figure B3a re-computes the Aitchison-distance LOWESS curve for $\varepsilon \in \{0.1, 0.5, 1.0, 2.0\}$ percentage points. The curve is essentially invariant above 20 % self-sufficiency, confirming that the decoupling pattern is not an artefact of the pseudo-count. The two metrics are also strongly correlated across the panel (Pearson r = 0.900), so the choice of metric affects individual country rankings but not the global picture.

Clustering procedure. Country archetypes (Section 4.2.3) are built from the 2022 production-mix vectors on the three families. The three share variables are first standardised (zero mean, unit variance) so that no single family dominates the distance computation. Agglomerative hierarchical clustering is then applied with Ward's linkage, which merges the pair of clusters that minimises the increase in within-cluster variance at each step. The dendrogram (Figure B1) is cut at six clusters, a level chosen to balance interpretability against within-cluster homogeneity and to yield economically meaningful archetypes (Table 4).

Principal-component projection. Principal-component analysis (PCA) is used only to visualise the clusters in two dimensions (Figure B2); it does not generate the clusters, which are defined entirely by the Ward procedure above. The first two components explain 94.7 % of the cross-country variance, so the two-dimensional projection faithfully represents the six-cluster solution.

B.2 Figures reproduced from the main text

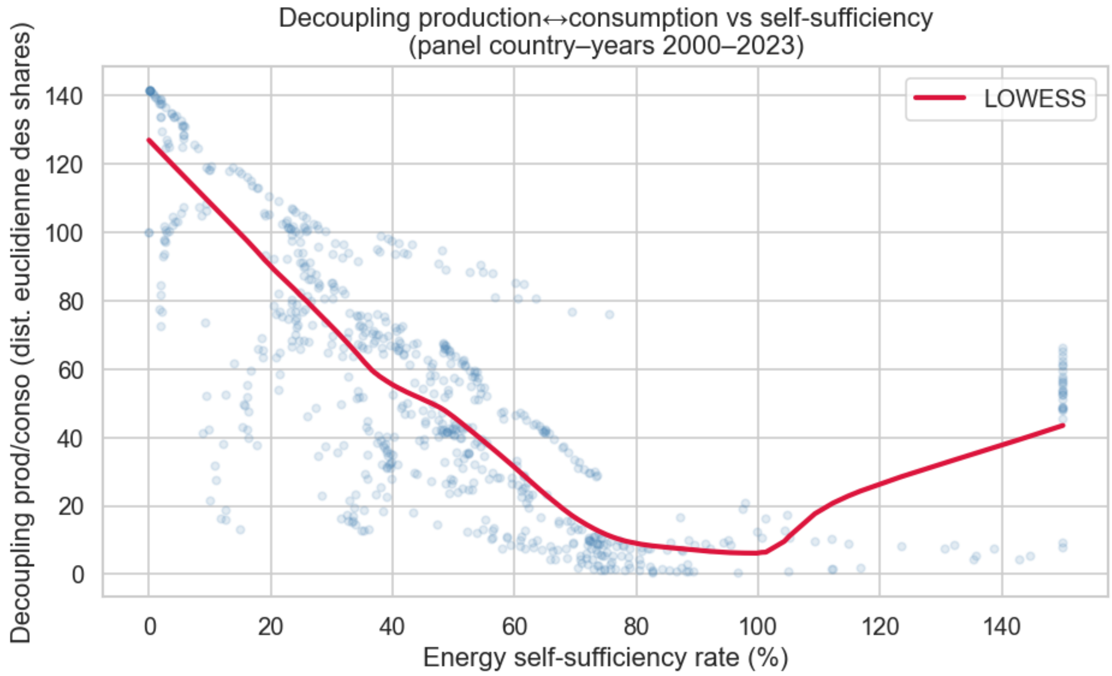


Figure 4.1 (reproduced). *Mix decoupling (Euclidean distance between the production and consumption mix) against the self-sufficiency ratio, with a LOWESS smoother. Each point is one country-year (2000-2023).*

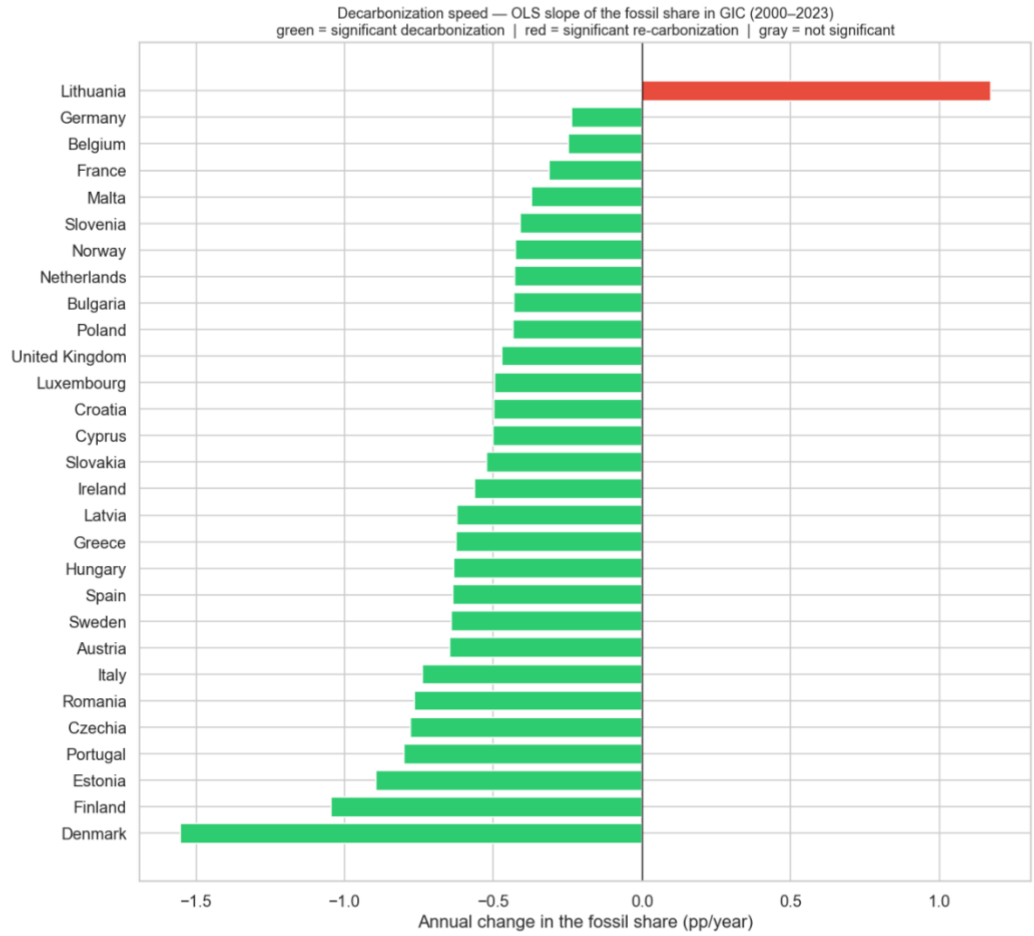


Figure 4.2 (reproduced). *OLS slope of the fossil consumption share against the year, by country (2000-2023). Green denotes significant decarbonisation, red significant re-carbonisation, grey a non-significant trend.*

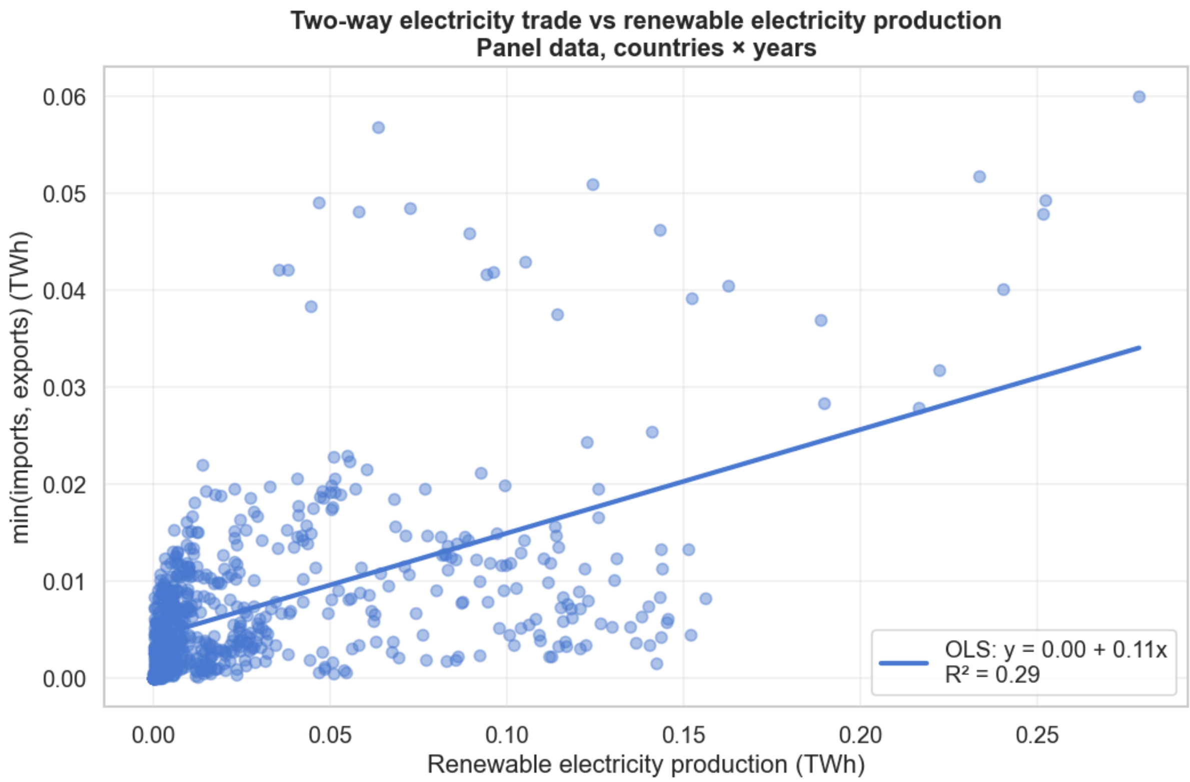


Figure 4.3 (reproduced). *Two-way electricity trade, measured as min(imports, exports) vs renewable electricity production, in TWh. Each point is one country-year; the line is the OLS fit with HC1-robust standard errors.*

B.3 Additional supporting figures

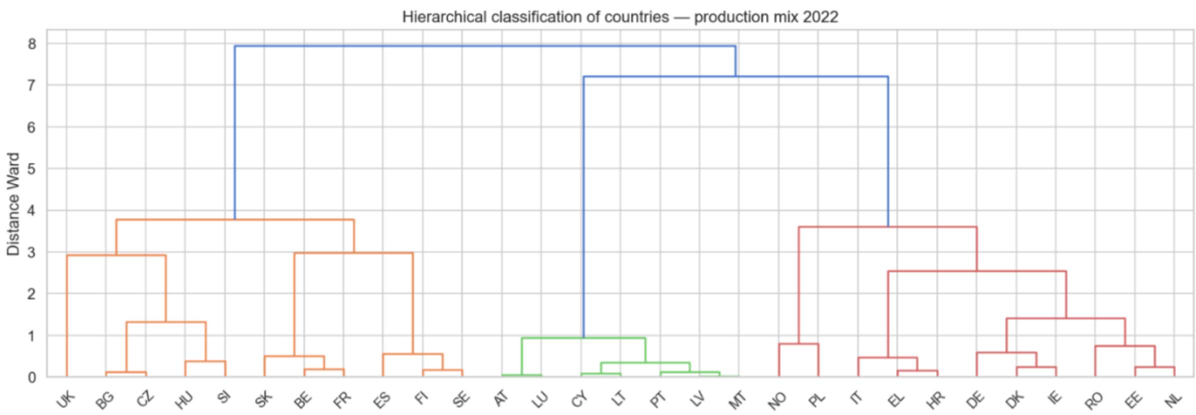


Figure B1. *Ward hierarchical clustering dendrogram on the standardised 2022 production-mix vectors. The cut into six clusters underlies the archetypes reported in Table 4.*

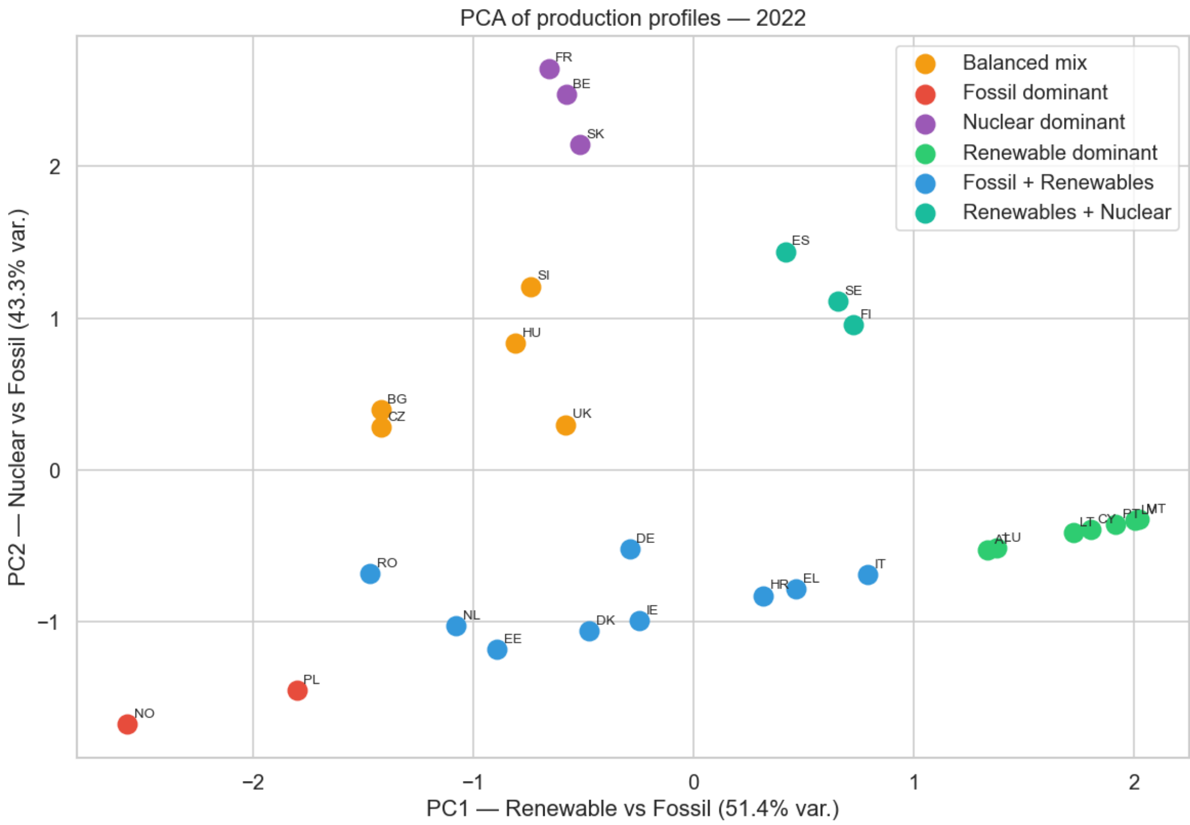


Figure B2. *Principal-component projection of country production-mix archetypes (2022), used for visualisation only. The two components explain 94.7 % of the cross-country variance; colours correspond to the six Ward clusters in Figure B1.*

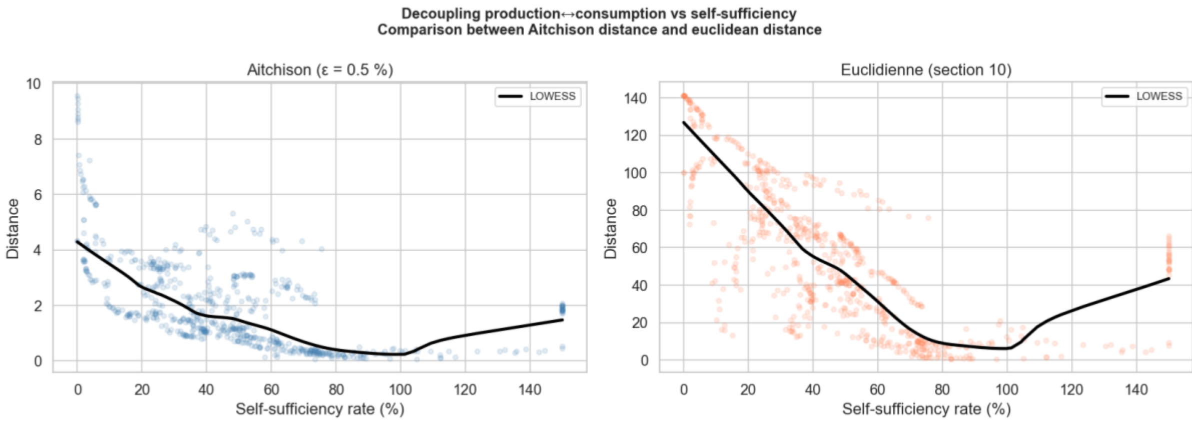


Figure B3. *Robustness comparison of the Aitchison and Euclidean mix-distance measures against self-sufficiency (Pearson r = 0.900 between the two series). Both recover the same decreasing-then-convex pattern.*

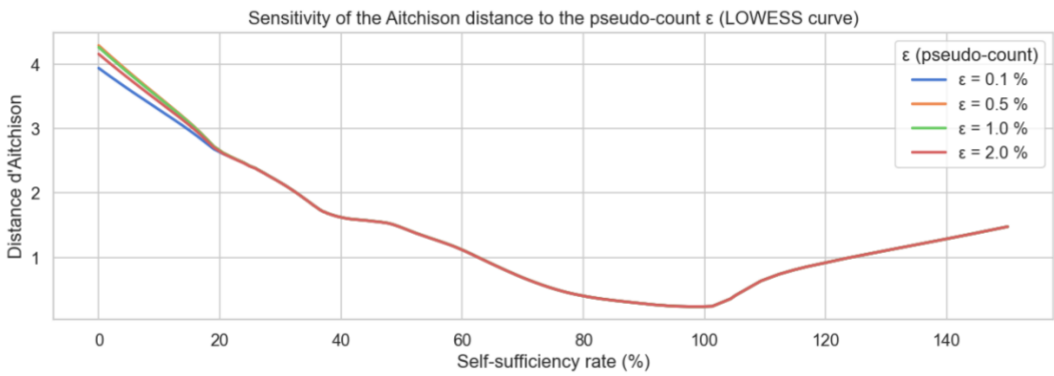


Figure B3a. *Sensitivity of the Aitchison-distance LOWESS curve to the pseudo-count ε used in the multiplicative zero replacement (ε = 0.1, 0.5, 1.0, 2.0 percentage points). The curve is invariant above 20 % self-sufficiency.*

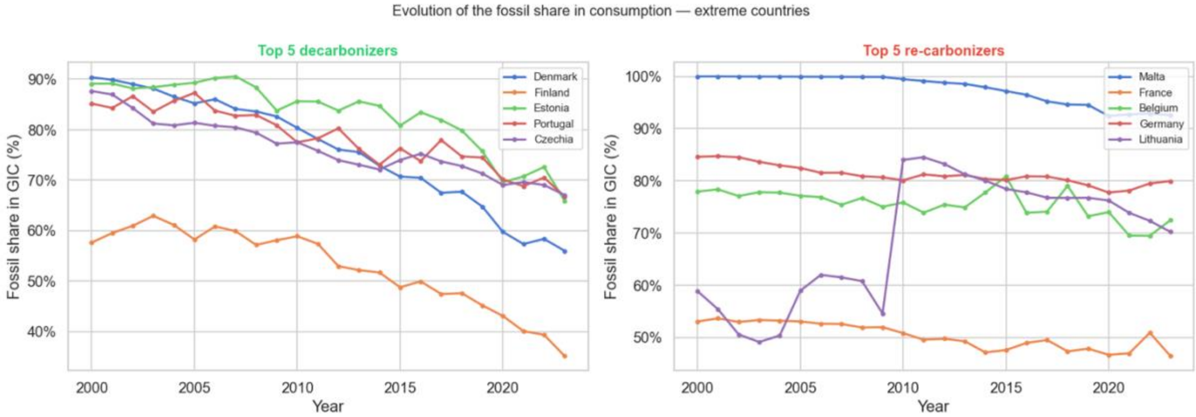


Figure B4. *Fossil consumption-share trajectories for the 5 fastest and 5 slowest decarbonisers (2000-2023).*

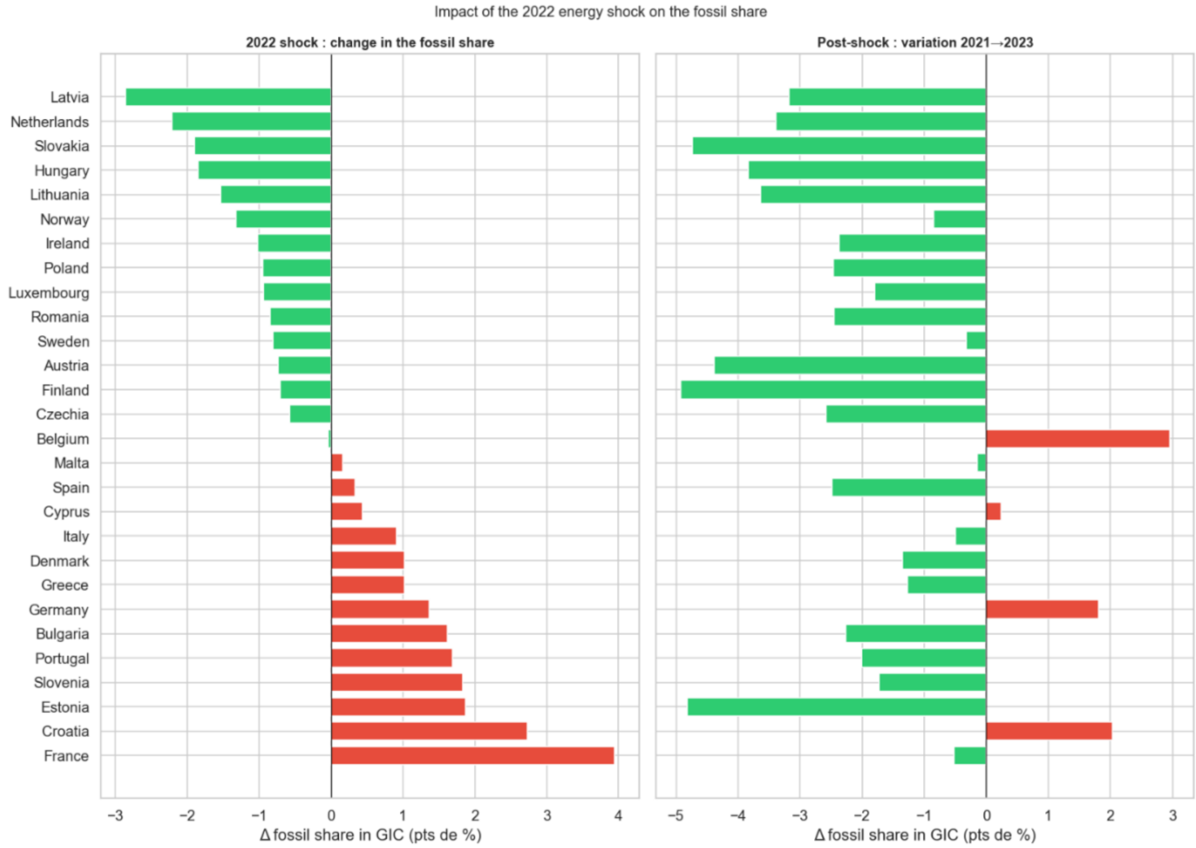


Figure B5. *Change in the fossil consumption share over 2021→2022 (left) and 2021→2023 (right). Green denotes a fall in the fossil share, red a rise. The post-shock panel shows the partial reversal by 2023.*

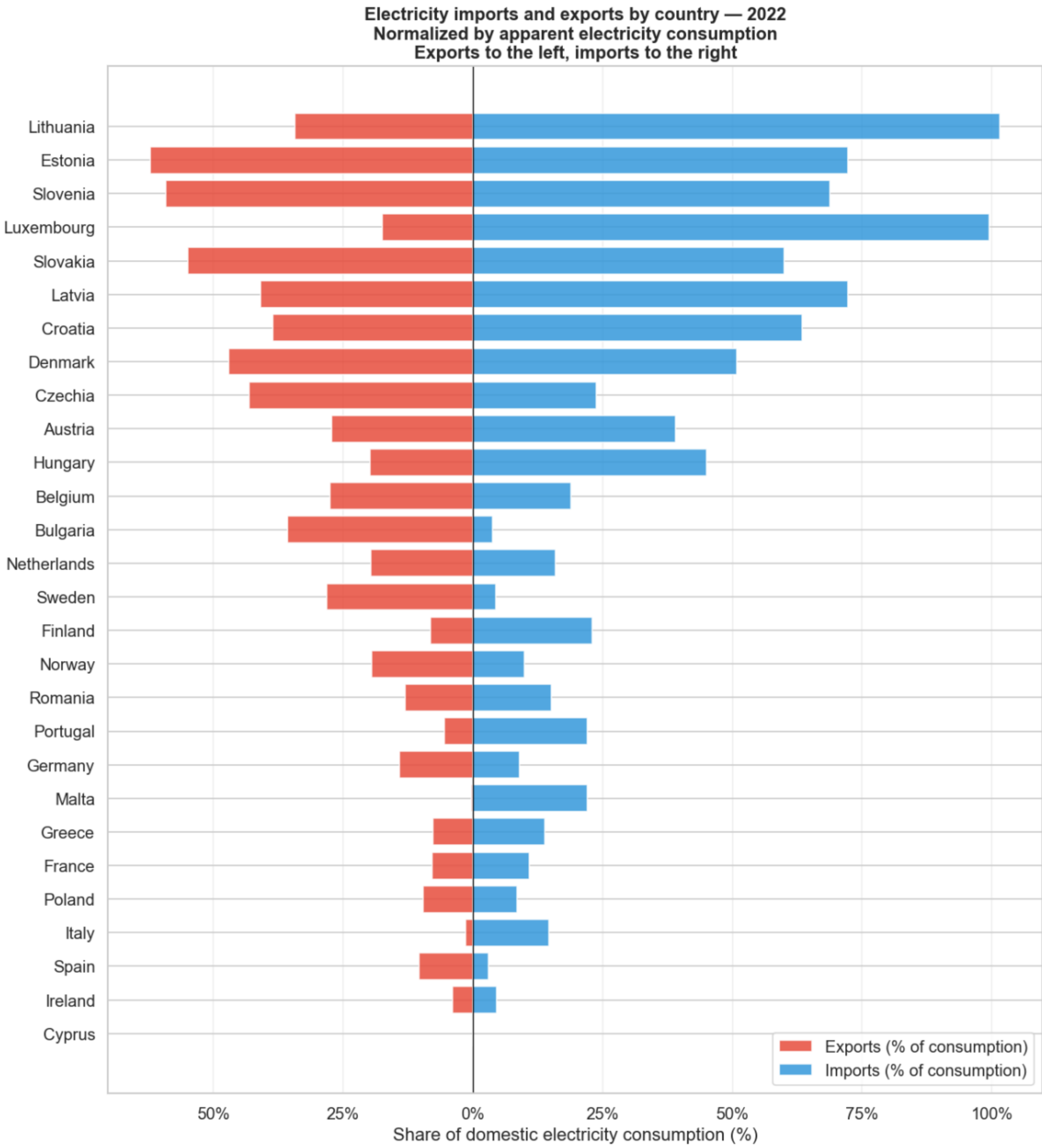
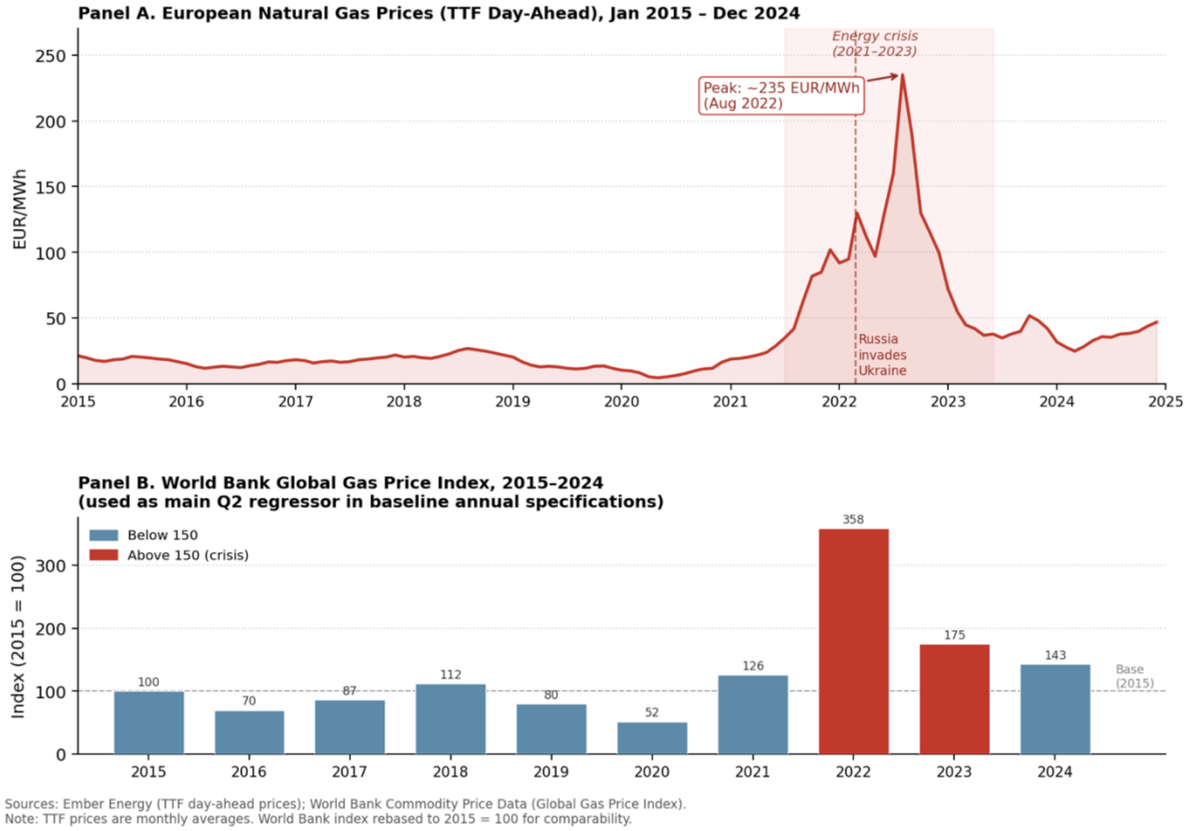


Figure B6. *Electricity imports and exports by country (2022), normalised by apparent domestic electricity consumption. Exports are shown to the left, imports to the right.*

Appendix C. Supporting Figures and Rolling Estimates for Section 4.4 (Q2)

This appendix collects the figures supporting the gas-price pass-through analysis in Section 4.4, including the panel-coverage map, descriptive scatter, model coefficient plots, the country-level pass-through distribution, the France-exclusion robustness check, and the rolling-window estimates referenced in Section 4.4.4. Unless stated otherwise, wholesale prices are from Ember Energy, the natural-gas price series from World Bank Commodity Price Data, and energy-mix shares are from Eurostat nrg_bal_c.

Figure 1. European natural gas prices and the World Bank global gas price index, 2015-2024.



Panel A shows monthly TTF day-ahead prices (EUR/MWh). Panel B shows the World Bank global gas price index, rebased to 2015 = 100. The annual version of this index is used as the main gas-price regressor in the baseline Q2 specifications. The shaded band in Panel A marks the 2021 to 2023 energy crisis window used in the robustness checks (Table 7).

Sources: Ember Energy; World Bank Commodity Price Data.

C.1 Consolidated robustness table

Table C1 reports the two interaction coefficients of interest gas×nuclear (top quartile) and gas×renewable (top quartile) across every specification, together with the standalone gas coefficient, the sample size and the fixed-effects structure. t-statistics (cluster-robust, by country) are in parentheses. The interaction terms are economically small and statistically insignificant throughout, with the single exception of the monthly gas × nuclear term, which is significant only in the full sample and collapses once the crisis window is removed.

Specification	Gas	Gas × Nucl Q4	Gas × Renew Q4	N	Fixed effects
Baseline annual (Model 3)	0.0501*** (24.05)	0.0034 (1.01)	0.0024 (0.81)	247	Country

Specification	Gas	Gas × Nucl Q4	Gas × Renew Q4	N	Fixed effects
Continuous-share interactions	0.0444*** (10.47)	0.0118 (1.60)	0.0059 (0.77)	247	Country
Country-specific trends (Model B)	0.0406*** (21.62)	—	—	247	Country + trends
Monthly (Model 3)	0.0446*** (26.94)	0.0041** (2.28)[b]	0.0005 (0.19)	2,919	Country
Monthly TWFE (Model 3 TWFE)	dropped	0.0020 (0.92)	0.0020 (0.85)	2,919	Country + month
Monthly, excl. 2022	0.0368*** (29.25)	0.0027 (1.32)	0.0003 (0.13)	2,619	Country
Monthly, excl. crisis window	0.0321*** (18.28)	−0.0002 (−0.05)	0.0001 (0.03)	2,364	Country
Monthly, lagged gas (t−1)	0.0473*** (28.82)	0.0040** (1.97)	0.0010 (0.37)	2,892	Country
France excluded (annual Model 3)	0.0496*** (23.68)	0.0041 (1.17)	0.0031 (1.04)	237	Country

Table C1. *Interaction coefficients across robustness specifications. Cluster-robust t-statistics (by country) in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. "dropped" indicates the standalone World Bank natural-gas price series is collinear with the time fixed effects and is not identified. The country-specific-trends specification (Model B) is reported as a robustness check for the standalone gas coefficient only; the interaction terms were not estimated under that specification (shown as "—"). [b] The full-sample monthly gas × nuclear term carries a wild cluster bootstrap p-value of 0.045 (B = 999, Rademacher weights, G = 27). The continuous-share specification replaces the top-quartile dummies with continuous nuclear and renewable shares.*

C.2 Definition of the country-level and rolling specifications

Country-level pass-through (Figure C5). The country-level estimates in Figure C5 come from a separate first-difference, log-log regression estimated country by country: Δ ln(wholesale price) regressed on Δ ln(country gas price), using the Eurostat country-level industrial gas price. The slope is therefore an elasticity (a percentage response to a one-percent change in the country gas price). It is not directly comparable to the panel pass-through coefficients in the main text, which regress the log wholesale price on the World Bank global gas index in levels; the two approaches measure related but distinct quantities and are reported as mutually supporting rather than identical.

Rolling estimates (Figures C7 and C8). The rolling coefficient is the standalone gas-price coefficient β from the monthly panel regression of the log wholesale price on the World Bank natural-gas price series, estimated on a moving 24-month window with country (entity) fixed effects and standard errors clustered by country. The shaded band is the 95 % confidence interval. It is the standalone pass-through coefficient, not a marginal effect from an interaction model. Figure C8 overlays the same rolling estimate computed on the sample excluding France.

C.3 Supporting figures

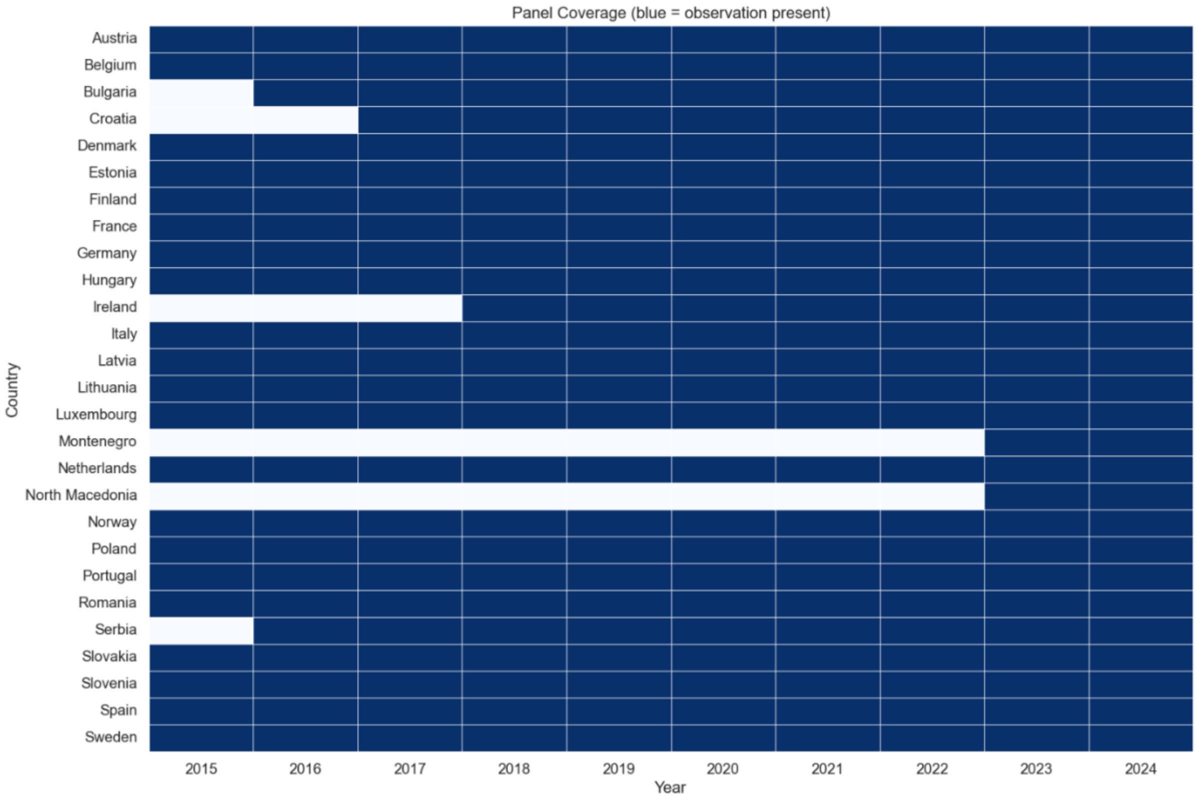


Figure C1. *Coverage of the Question 2 panel by country and year (blue = observation present). The unbalanced structure reflects missing wholesale price data for Bulgaria, Croatia, Ireland and Montenegro in the earlier years.*

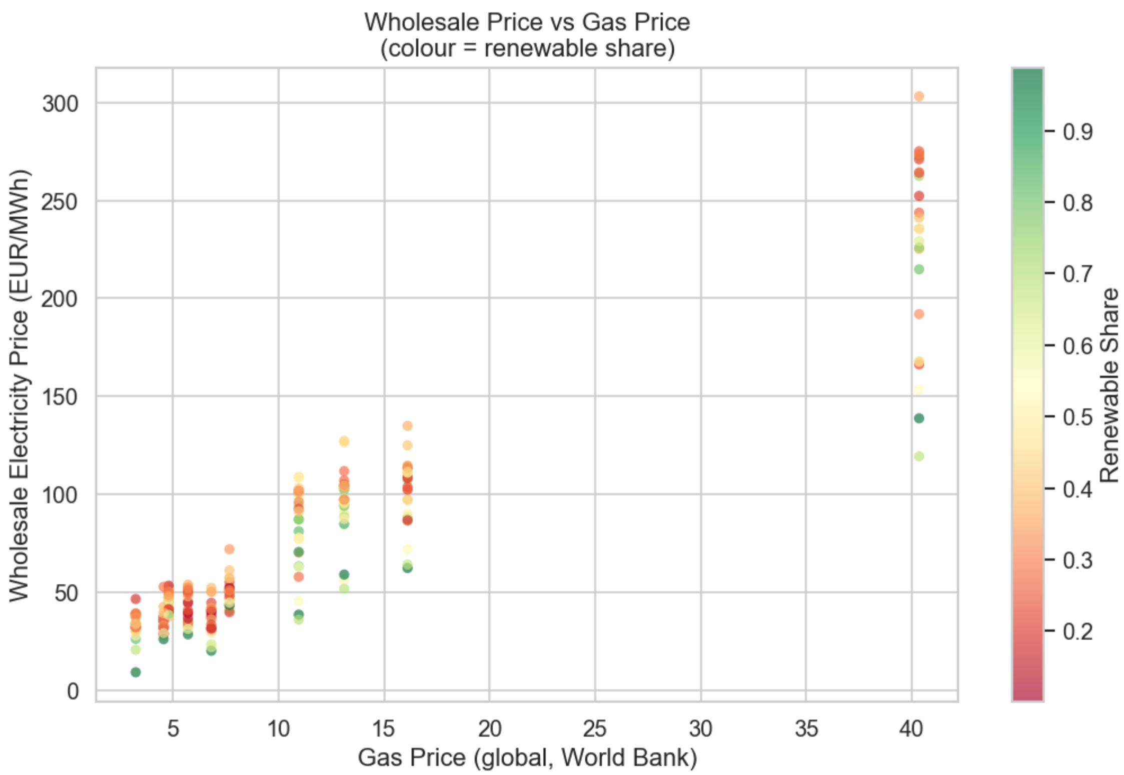


Figure C2. *Wholesale electricity price (EUR/MWh) against the World Bank natural gas price series*

(USD/MMBtu), with points coloured by renewable share. The strong positive relationship holds across the renewable-share distribution.

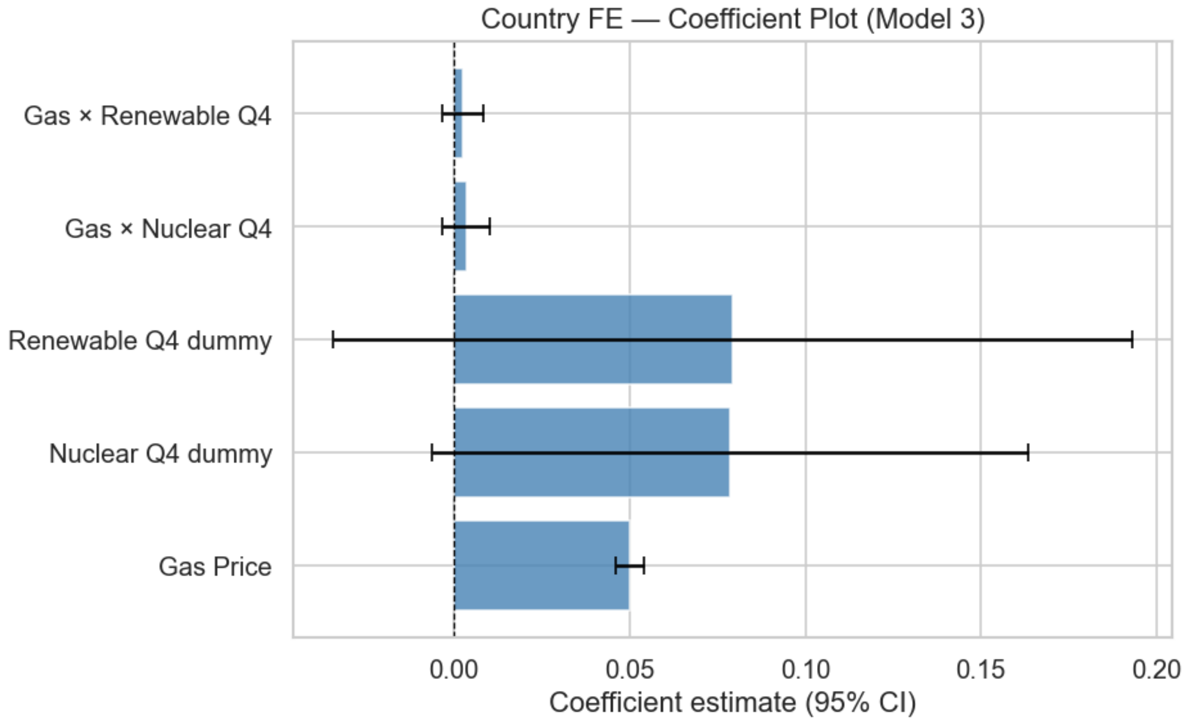


Figure C3. *Coefficient plot for the interaction model (Model 3, country fixed effects, cluster-robust 95 % intervals). The gas-price coefficient is precisely estimated and positive, while the two interaction terms are statistically indistinguishable from zero.*

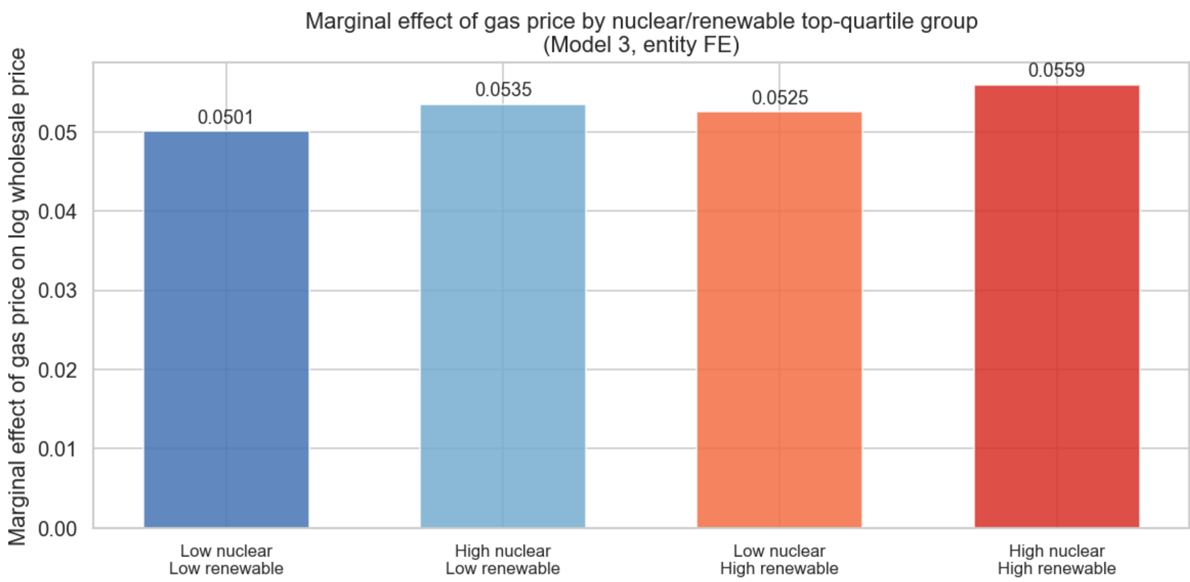


Figure C4. *Marginal effect of the gas price on the log wholesale price by top-quartile nuclear and renewable group (Model 3, country fixed effects). The four marginal effects are close (0.0501 to 0.0559), indicating no meaningful insulation from gas movements.*

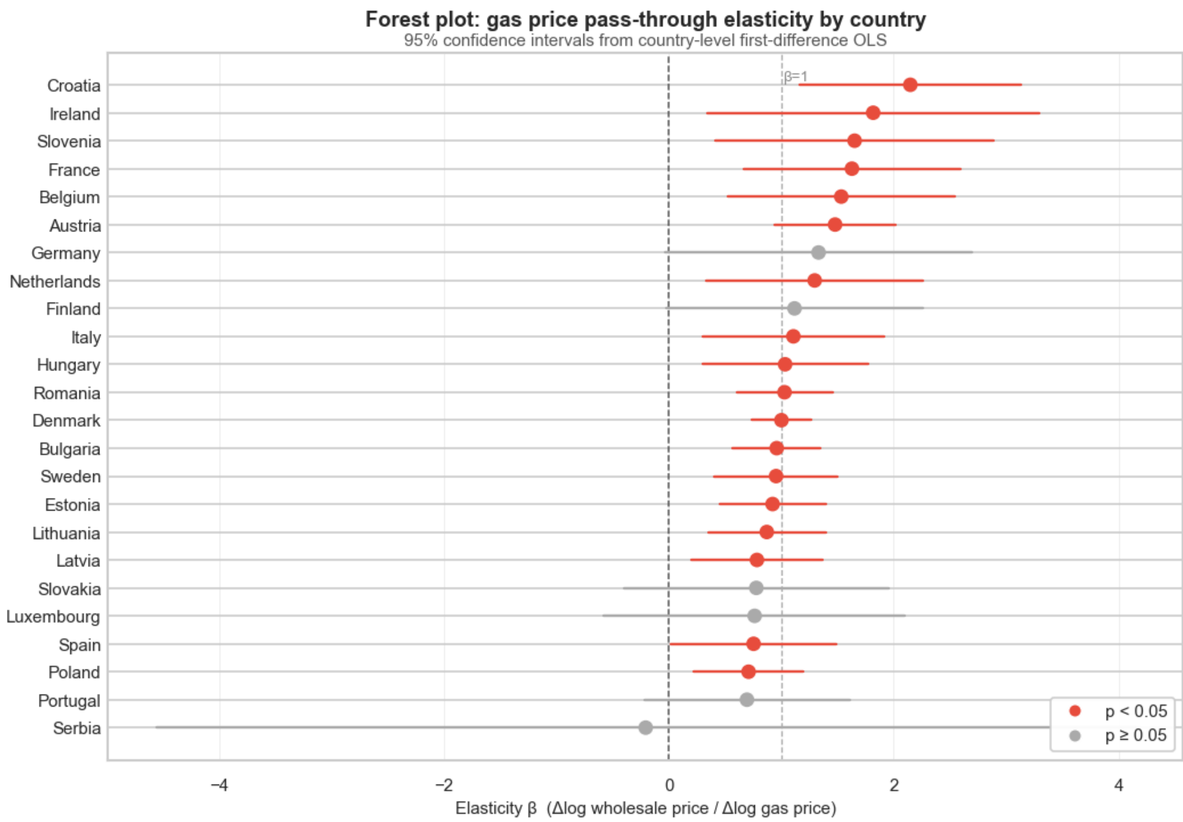


Figure C5. *Country-level gas-price pass-through elasticity with 95 % confidence intervals, from a first-difference log-log OLS estimated country by country: Δ ln(wholesale price) on Δ ln(country gas price). The reference line marks β = 1. These elasticities are not directly comparable to the panel log-level coefficients (see Section C.2).*

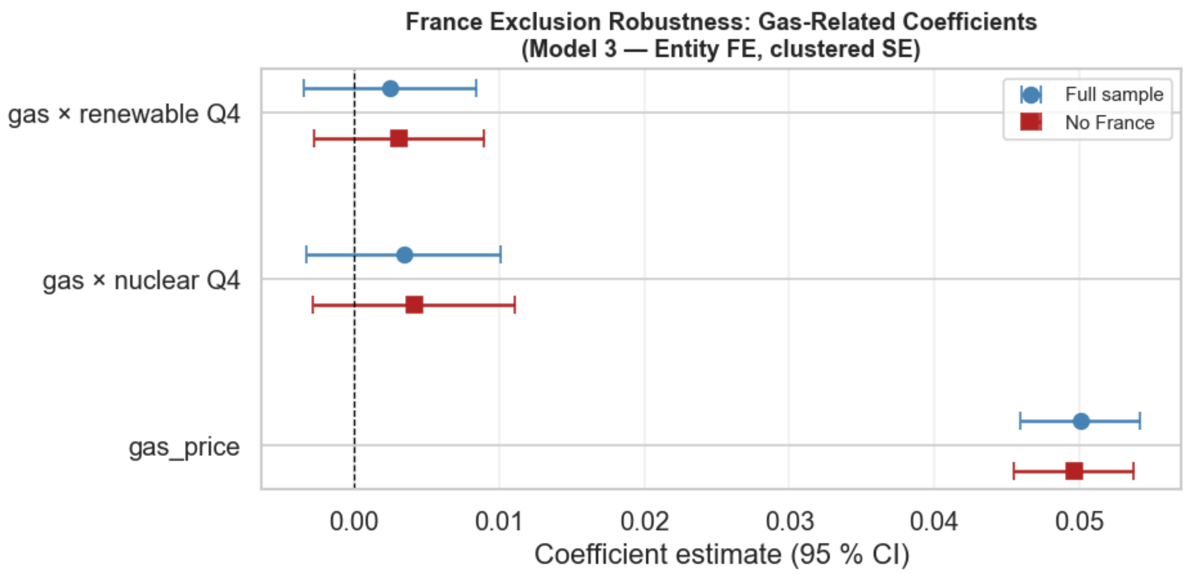


Figure C6. *Gas-related coefficients (annual Model 3, country fixed effects, cluster-robust 95 % intervals) for the full sample and with France excluded and quartiles recomputed. The gas-price coefficient and both interaction terms are virtually unchanged, confirming that the results are not driven by France.*

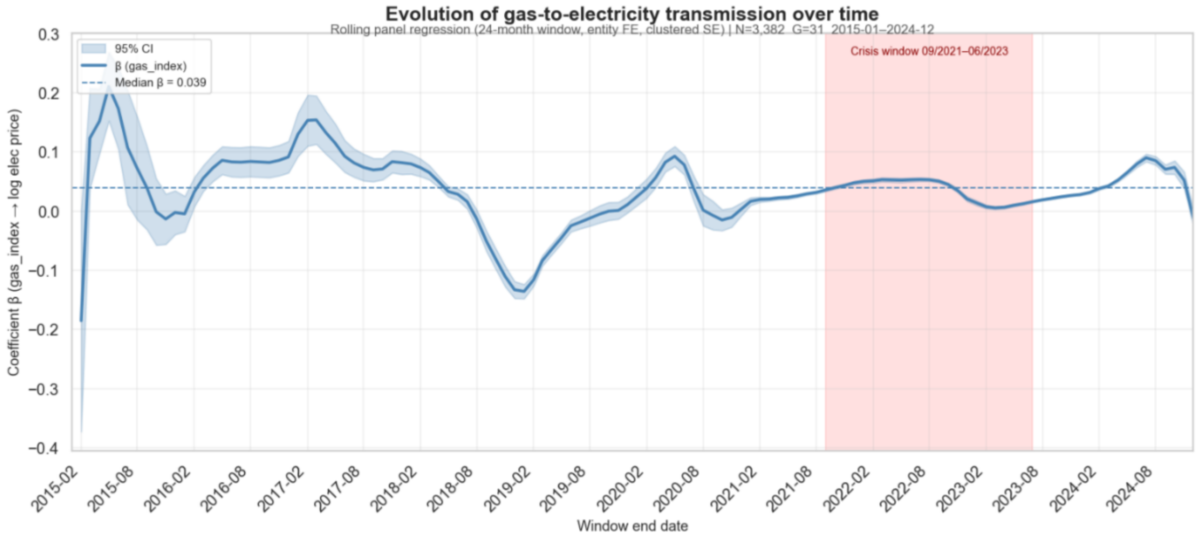


Figure C7. *Rolling 24-month estimate of the standalone gas-price coefficient β from the monthly panel regression of the log wholesale price on the World Bank natural-gas price series (country fixed effects, standard errors clustered by country), with a 95 % confidence band. The shaded area marks the September 2021 to June 2023 crisis window; the median β over the sample is 0.039.*

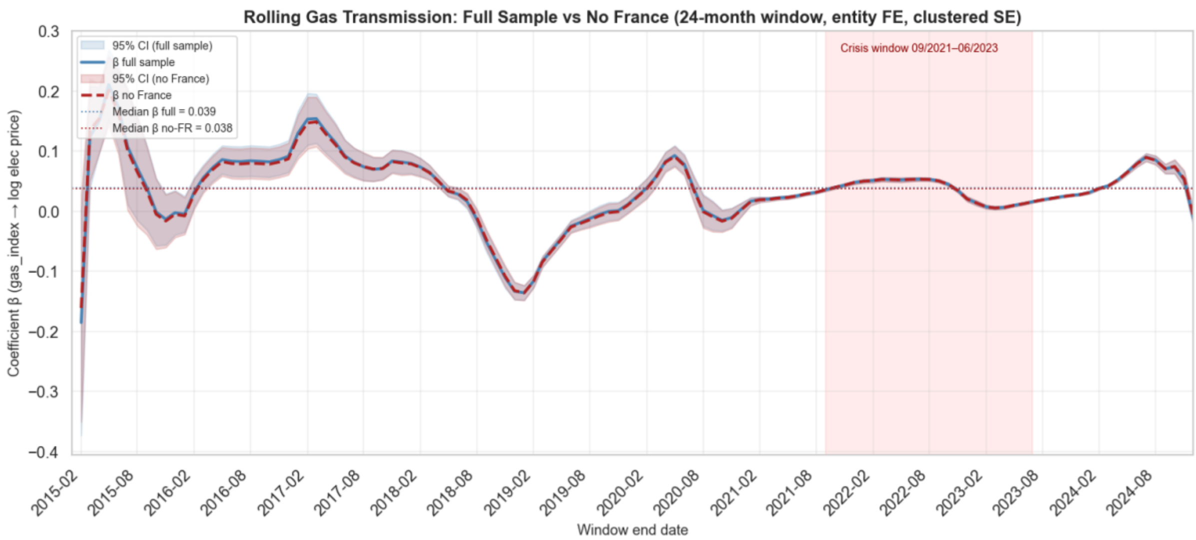


Figure C8. *Rolling 24-month standalone gas coefficient β (specification as in Figure C7) for the full sample and excluding France. The two paths are nearly identical (median β of 0.039 versus 0.038), confirming that France's 2022 reactor outages do not drive the aggregate pass-through pattern.*