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Fuel Switching and Energy Security: Evidence from Gas–Coal Substitution in European Electricity Generation

Yican Liu

Harris School of Public Policy, University of Chicago, Chicago, USA
ycliu3c3@uchicago.edu

Abstract. The European energy crisis, exacerbated by the Russia–Ukraine conflict, exposed the fragility of gas-dependent power systems and underscored the urgent need to understand short-term substitution dynamics between conventional fossil fuels. While renewable energy is the long-term solution for decarbonization, near-term resilience depends on the balance between gas and coal. This study examines coal–gas substitution in European electricity generation, focusing on how relative fuel prices and carbon pricing influence generation patterns. A monthly panel of 27 EU member states from 2015 to 2024, the research employs fixed-effects models to estimate substitution effects, with robustness checks incorporating carbon-inclusive costs and heterogeneity tests by fuel structure and crisis periods. Results show that a 1% increase in the relative gas–coal price reduces the gas share by about 0.11, while a €10/t rise in the carbon price raises it by roughly 1.4 percentage points. Carbon pricing amplifies responsiveness to relative prices, with stronger substitution in high gas-share and low coal lock-in countries, whereas crisis conditions preserved price effects but weakened policy impacts. These findings provide new evidence on short-term resilience and inform strategies to enhance flexibility and reduce structural dependence.

Keywords: Fuel switching, Gas–coal substitution, Relative fuel prices, Electricity generation, Energy security

1. Introduction

In recent years, the global energy market has been destabilized by successive shocks, with the 2022 outbreak of the Russia–Ukraine conflict triggering an acute crisis in Europe's natural gas supply. This event not only exposed Europe's heavy reliance on fossil fuels in its power system but also underscored the vulnerabilities of its energy security, making clear the urgent need for systematic assessments of resilience under crisis conditions. While renewable energy is widely recognized as the long-term pathway to decarbonization and enhanced security, it cannot be expanded rapidly during crises. In the short run, therefore, the balance between traditional fossil fuels, particularly natural gas and coal, remains crucial for maintaining power supply stability and managing carbon emissions. Natural gas, often viewed as a "bridge fuel" in the energy transition, faces risks from price volatility and geopolitical disruptions, raising a pressing policy question: when gas supply is constrained, can coal temporarily regain importance as a substitute, and what does this imply for designing effective energy security strategies? Against this backdrop, this paper examines how the European power sector responds to gas supply constraints by analyzing the substitution dynamics between natural gas and coal, with particular attention to how relative fuel prices and carbon pricing influence generation patterns. The study

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examines how relative fuel prices, including adjustments in carbon pricing, influence generation patterns and situates this mechanism within the broader discourse on energy security. To address this, the study uses monthly panel data from 27 EU member states spanning 2015 to 2024, estimating fixed-effects models with a robustness check incorporating carbon-inclusive costs. Further heterogeneity analyses explore differences across gas capacity levels, coal dependency, and crisis periods. This study makes two contributions. First, it provides cross-country empirical evidence on fossil-fuel substitution mechanisms, complementing prior work that has focused primarily on renewable energy's long-term role or single-country case studies. Second, by embedding gas–coal substitution within the framework of energy security, it highlights how traditional fuel dynamics remain central to understanding system stability under market stress.

2. Literature review

The intersection of the energy transition and energy security has emerged as a central theme in academic discourse. Many studies stress that renewable energy lowers emissions and external dependence, making it a core pathway to strengthen security. Khan et al. add that renewables improve security but also create risks through climate variability and uneven policy frameworks [1]. Tugcu and Menegaki, along with Kim et al., likewise find that renewable expansion can bolster security if backed by investment, though short-term effects remain limited [2,3]. Overall, this literature highlights the long-term benefits of renewables but offers little evidence on short-term stability under supply shocks.

In contrast, short-term power system stability often depends on fuel switching between natural gas and coal, yet systematic research on these dynamics is scarce. Most existing evidence comes from single-country studies, primarily focused on the United Kingdom. Wilson and Staffell show that Britain's carbon pricing drove rapid coal-to-gas switching and major emission reductions in 2016, while Gugler et al. confirm that the UK carbon tax reshaped marginal costs, pushing coal out and making gas more competitive [4,5]. Other contributions rely on simulation models. Delarue et al., using E-Simulate, highlight the role of gas–coal price ratios during the first EU ETS phase, while Böhringer and Rosendahl apply a general equilibrium model to coal phaseout scenarios [6,7]. Broader evidence is limited: Pettersson et al. analyze eight European countries and find short-run substitution driven mainly by relative prices and policies [8]. Still, these studies largely focus on efficiency or emission reduction and draw on historical data, leaving recent crisis dynamics unexamined.

This gap is especially salient in the European energy crisis, where geopolitical shocks exposed vulnerabilities in gas supply. Existing work has not directly examined coal–gas substitution under such conditions or the heterogeneity across national energy structures and generation capacity.

3. Data

3.1. Data source and sample

The research compiled a monthly panel dataset for 27 EU member states from 2015 to 2024, integrating fuel prices, electricity statistics, and weather indicators. Fuel prices are from the World Bank Pink Sheet (natural gas, \$/mmbtu; coal, \$/mt) and EU ETS allowance prices are from Investing.com (€/tCO_2) [9,10]. Electricity data from Ember include generation by fuel type (TWh), total generation, demand (TWh), and the renewable share (%) [11]. Climate conditions are proxied by heating and cooling degree days (HDD and CDD) from Eurostat [12]. The sample covers the 27 EU member states over 2015–2024, spanning both pre-crisis years and the 2021–2023 energy shock. A few countries lack data in the early period (2015–2016). To avoid interpolation-induced noise, these missing entries are left as is; since they are non-systematic, they do not compromise the validity of results. The final dataset consists of 3,038

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country-month observations, forming an unbalanced monthly panel with broad cross-sectional and temporal coverage.

3.2. Dependent variables

The dependent variable is the gas–coal substitution share ($\mathrm{GasCoalShare_{it}}$), which captures the relative utilization of natural gas and coal in the power sector. It is defined as:

$$\mathrm{GasCoalShare_{it}} = \frac{\mathrm{Gas_{it}}}{\mathrm{Gas_{it}}+\mathrm{Coal_{it}}} \tag{1}$$

where $\mathrm{Gas_{it}}$ denotes electricity generation from natural gas in country i and month t, and $\mathrm{Coal_{it}}$ covers both hard coal and lignite. Restricting the denominator to gas and coal isolates their direct competition, avoiding confounding from renewables or nuclear. This measure reflects the short-term role of conventional fuels under crisis conditions and serves as a consistent indicator of substitution dynamics. The variable is expressed as a ratio ranging from 0 to 1, which can be interpreted in percentage terms.

3.3. Key independent variables

The first key independent variable is the relative price of natural gas to coal ($\mathrm{ln\_real\_price_t}$), capturing their competitiveness. It is defined as the logarithm of the price ratio:

$$\mathrm{ln\_real\_price_t} = ln\left(\mathrm{GasPrice_t}\right) - ln(\mathrm{CoalPrice_t}) \tag{2}$$

where $\mathrm{GasPrice_t}$ is in U.S. dollars per million British thermal units (\$/mmbtu) and $\mathrm{CoalPrice_t}$ in U.S. dollars per metric ton (\$/mt). Values were standardized across units to ensure comparability. The logarithmic form reduces skewness and allows coefficients to be interpreted as elasticities. This measure summarizes relative market competitiveness and serves as the primary driver of coal–gas substitution.

The second variable is the carbon price ($\mathrm{carb\_std}$), measured as the EU ETS allowance price ($€/\mathrm{t\ CO_2}$). Standardization ensures comparability across regressors. Since coal has a higher emission factor than gas, rising carbon prices disproportionately increase coal costs, thereby enhancing the competitiveness of natural gas and promoting fuel substitution.

The third variable is the interaction term ($\mathrm{int\_relprice\_carb_t}$), defined as the product of relative price and carbon price:

$$\mathrm{int\_relprice\_carb_t} = \mathrm{ln\_real\_price_t} \times \mathrm{carb\_std_t} \tag{3}$$

This captures whether carbon pricing amplifies price-driven substitution. The coefficient is dimensionless and reflects the moderating role of carbon policy in strengthening responsiveness of fuel choice to relative price signals.

3.4. Control variables

In the baseline regressions, four control variables are included: electricity demand (logarithm of monthly generation), renewable share (proportion of renewables in total generation), heating degree days (HDD), and cooling degree days (CDD). These, along with country and month fixed effects, account for demand, renewable penetration, and seasonal variation. Table 1 presents descriptive statistics for these variables, including observations, mean, standard deviation, and range, providing an overview of their magnitude and variation.

Table 1. Descriptive statistics of main variables

Variable	N	Mean	Std.Dev	Min	Max
GasCoalShare	2,687	0.626	0.340	0.000	1.000
ln_rel_price	3,037	-2.563	0.337	-3.506	-1.495
carb_std	3,037	-0.093	1.001	-1.259	1.758
log_demand	3,037	1.375	1.306	-1.470	4.044
renewable_share	3,037	0.393	0.235	0.000	1.000
HDD	3,037	226.204	200.366	0.000	968.200
CDD	3,037	10.886	33.457	0.000	291.190

4. Empirical strategy and model design 900

4.1. Baseline model

This study employs a country–month panel regression model for European power markets to analyze how relative fuel costs influence short-term substitution between coal and natural gas. This specification captures the immediate response of fuel choice to price signals and policy factors, particularly under crisis conditions where energy supply security is threatened.

Formally, the model is expressed as:

$$GasCoalShare_{i,t} = \beta_0 + \beta_1 \ln\_real\_price_{i,t} + \beta_2 carb\_std_{i,t} + \beta_3 int\_relprice\_carb_t + \gamma' X_{i,t} + \mu_i + \sum_{m=2}^{12} \delta_m D_m$$

where $GasCoalShare_{i,t}$ represents the share of natural gas in total coal–gas generation for country i in month t. The regressors include the relative gas–coal price ($\ln\_real\_price_{i,t}$), the standardized carbon price ($carb\_std_{i,t}$), and their interaction term, while $X_{i,t}$ denotes controls for electricity demand, renewable share, and HDD/CDD. μ_i denotes country fixed effects, capturing time-invariant heterogeneity. Seasonal demand and supply patterns are controlled through a set of monthly dummies, $\sum_{m=2}^{12} \delta_m D_m$.

Within this framework, two model specifications are estimated. Model 1 (No Controls) includes only the key explanatory variables, fixed effects, and monthly dummies, providing a parsimonious setup to identify fundamental price - driven substitution. Model 2 (Controls) extends this baseline by adding demand, renewable share, and weather variables, thereby mitigating omitted variable bias and serving as the preferred specification.

A fixed-effects estimator is adopted to account for unobserved time-invariant heterogeneity across countries—such as resource endowments, policy regimes, and grid structures—while monthly dummies control for recurring seasonal cycles. Compared to random- or mixed-effects models, this approach is better suited to multi-country panels and ensures coefficients reflect the marginal effects of relative prices and carbon costs on gas–coal substitution.

4.2. Identification strategy and hypotheses

The identification strategy relies on the fact that relative fuel prices in Europe are determined by international commodity markets and the EU Emissions Trading System, rather than by countries' short-term generation mixes [13]. Country fixed effects absorb time-invariant heterogeneities such as resource endowments, policy regimes, and grid infrastructure, while monthly dummy variables capture seasonal fluctuations in energy supply and demand. Control variables for electricity demand, renewable share,

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and climate conditions further mitigate omitted-variable bias. Year–month fixed effects are excluded because fuel and carbon prices exhibit strong common monthly variation across Europe; including them would absorb these signals and undermine identification.

To address potential overlap between policy interventions and price shocks during the energy crisis, robustness checks incorporate crisis-period interaction terms and carbon-inclusive relative price measures. Since fuel and carbon prices are set at international or EU levels, they are unlikely to be simultaneously determined by individual countries' short-term fuel usage, reducing the risk of estimation bias [14].

Within this framework, three hypotheses are proposed:

•H1: The coefficient on relative gas–coal prices is negative, as higher gas prices reduce gas's share in combined generation.

•H2: The coefficient on carbon prices is positive, as higher carbon costs penalize coal and enhance gas competitiveness.

•H3: The coefficient on the interaction term is positive, indicating that carbon pricing amplifies price-driven substitution.

4.3. Robustness check

To ensure the robustness of the baseline results, a carbon-inclusive measure of fuel competitiveness is constructed, incorporating the EU ETS cost into effective fuel costs. The variable is defined as

$$\mathrm{relcost_t} = ln\left(\frac{\mathrm{GasPrice_t + EF^{Gas} \times CO_2Price_t}}{\mathrm{CoalPrice_t + EF^{Coal} \times CO_2Price_t}}\right) \quad (5)$$

Where $\mathrm{CO_2Price_t}$ is the EU ETS allowance price, while $\mathrm{EF^{Gas}} = 0.37\ \mathrm{tCO/MWh}$ and $\mathrm{EF^{Coal}} = 0.9\mathrm{tCO/MWh}$ are the emission factors reflecting the average carbon intensity of gas- and coal-fired power generation [15,16]. This specification approximates the effective marginal cost comparison faced by generators, since carbon costs directly enter short-run marginal costs in European power markets.

The author then re-estimate the fixed-effects specification of Section 4.1, replacing all three key independent variables with $\mathrm{relcost_t}$ while keeping all controls, fixed effects, and clustered standard errors unchanged. The coefficient on $\mathrm{relcost_t}$ is expected to be negative: a higher carbon-inclusive cost of gas relative to coal should reduce the gas share in coal–gas generation. If the estimated coefficient remains consistent in sign and magnitude with the baseline results, it confirms that the observed coal–gas substitution is driven by fundamental price signals rather than the specific choice of relative price metric.

4.4. Heterogeneity

In the baseline specification, the analysis estimates the average effect of relative fuel prices and carbon costs on coal–gas substitution. Yet such averages may conceal heterogeneity across European countries.

Structurally, countries are categorized based on two dimensions: their dependence on natural gas and the degree of coal lock-in. Based on baseline gas shares, the sample is divided into high- and low-gas groups. In high-gas systems, price signals are expected to exert stronger influence on generation choices, while in low-gas systems the effect is more muted. A similar split is made for coal lock-in, measured as the share of coal in combined coal–gas generation. In countries with high coal lock-in, substitution margins are constrained, limiting the responsiveness to cost shifts; in low-lock-in countries, changes in relative prices are more readily transmitted to the generation mix. These comparisons illustrate how structural conditions mediate the responsiveness of substitution to market signals.

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Contextually, the analysis incorporates the European energy crisis. The period from October 2021 to March 2023 is defined as the crisis window, and interaction terms between this indicator and the price variables are included. If effects are amplified during this interval, it would suggest that external shocks heightened the salience of cost signals, making fuel switching a more immediate mechanism for maintaining energy supply security.

5. Result and discussion

Table 2. Regression results

	Dependent variable:							
	Gas-to-Coal Generation Share							
	Model 1	Model 2	Model 3	High GasShare	Low GasShare	High Coal Lock-in	Low Coal Lock-in	Crisis interactions
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(Relative gas/coal price)	-0.116***	-0.106***		-0.109***	-0.095***	-0.104***	-0.094***	-0.082***
	(0.019)	(0.016)		(0.023)	(0.019)	(0.018)	(0.026)	(0.014)
Carbon price (std.)	0.142***	0.144***		0.187***	0.073	0.170*	0.116***	0.237***
	(0.037)	(0.038)		(0.053)	(0.043)	(0.072)	(0.033)	(0.049)
Rel. price × Carbon	0.029***	0.034**		0.048**	0.012	0.043	0.027**	0.064***
	(0.011)	(0.012)		(0.016)	(0.015)	(0.024)	(0.009)	(0.015)
log(Demand)		-0.090	-0.146	0.027	-0.359*	0.069	-0.308	-0.097
		(0.114)	(0.138)	(0.119)	(0.161)	(0.053)	(0.164)	(0.113)
Renewables share		0.149*	0.283***	0.167*	0.045	0.300**	0.076	0.100
		(0.071)	(0.082)	(0.082)	(0.070)	(0.110)	(0.063)	(0.067)
HDD		0.00007	0.00009	0.00015	-0.00006	0.00031**	-0.00002	0.00005
		(0.00008)	(0.00008)	(0.00008)	(0.0001)	(0.0001)	(0.00007)	(0.00008)
CDD		0.00010	0.00014	-0.00019	-0.00013	-0.00003	0.00045*	0.00012
		(0.00023)	(0.00027)	(0.00022)	(0.0003)	(0.0003)	(0.00022)	(0.00023)
ln(Rel price) × Crisis								-0.010
								(0.010)
Carbon × Crisis								-0.076***
								(0.019)
Relative carbon cost			0.132***					
			(0.030)					
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Clustered SE	Country	Country	Country	Country	Country	Country	Country	Country
Observations	2687	2687	2687	1638	1049	1261	1426	2687

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Table 2. (continued)

R2	0.289	0.301	0.213	0.379	0.247	0.414	0.268	0.325
Note:	Standard errors clustered at the country level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$							

5.1. Baseline results

Table 2 presents the baseline estimation results. The coefficients are consistent with theoretical expectations and robust across different model specifications. The relative gas–coal price has a negative and highly significant coefficient (–0.116 to –0.106), confirming that when natural gas becomes more expensive relative to coal, the share of natural gas in combined coal–gas generation decreases. The carbon price is positive (around 0.14) and strongly significant, showing that higher carbon costs reduce coal's competitiveness and favor gas. The interaction term is also significantly positive (0.029–0.034), indicating that carbon pricing reinforces the effect of relative prices, making substitution more price-elastic under higher carbon costs. These results are stable across Model A and the main specification, underscoring the robustness of the core substitution mechanism.

Control variables display weaker effects. Electricity demand enters with a negative but insignificant coefficient, suggesting that scale effects are not central to substitution dynamics. The renewable share becomes positive and significant once added, implying that gas complements renewable integration while coal is more easily displaced. By contrast, climate indicators show no significant effect, indicating that short-term weather fluctuations do not substantially alter coal–gas substitution.

5.2. Robustness checks

In the robustness check, the carbon-inclusive measure of relative cost is used in place of the baseline relative price variable. The results show that the coefficient of the relative carbon cost is 0.160, statistically significant at the 1 percent level. This positive coefficient is consistent with expectations: a higher carbon price increases the relative cost of coal-fired generation, thereby enhancing the competitiveness of natural gas and raising its share in combined coal–gas generation. The finding indicates that the conclusion on price-driven substitution does not hinge on the specific definition of fuel price, underscoring the robustness of the empirical results.

5.3. Heterogeneity analysis

In countries with high gas shares, gas-fired capacity and operational infrastructure are more developed, making these systems more responsive to market and policy signals. Results show that coefficients for relative fuel prices and carbon prices are both significant (-0.109***, 0.187***), and the interaction term is also positive and significant (0.048**), indicating that carbon pricing amplifies the effect of relative fuel costs. By contrast, in low gas-share countries, the coefficient on relative prices remains significant and negative (-0.095***), but carbon prices and the interaction term are insignificant (0.073, 0.012). This suggests that substitution elasticity is constrained by system and infrastructure limitations. The findings align with expectations and highlight the importance of preparedness for energy security: market and policy signals can only translate into actual substitution where sufficient gas capacity exists.

Differences in coal dependence produce a similar asymmetry. In high coal lock-in countries, the price effect remains negative and significant, but the influence of carbon pricing and the interaction term weakens (0.170*, 0.043), showing that strong coal dependence reduces the effectiveness of carbon signals. In contrast, low coal lock-in countries exhibit much greater flexibility: the coefficient of carbon prices is positive and significant (0.116***) and the interaction term is likewise positive (0.027**). This finding suggests that coal dependence not only implies higher emissions but also reduces adaptive

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capacity under crisis conditions. It echoes the “lock-in effect” discussed in the energy security literature, where structural dependence exacerbates vulnerability to external shocks [17].

During the crisis window, the interaction of relative prices with the crisis dummy is insignificant (-0.010), indicating stable substitution elasticity. By contrast, the carbon–crisis interaction is negative and significant (-0.076***), showing that the crisis curtailed the effect of carbon pricing. While market signals continued to operate, policy-based instruments lost part of their effectiveness, likely because interventions and supply constraints impeded transmission [18].

Overall, the coal–gas substitution mechanism is robust but uneven: market signals operate consistently across different contexts, while the adaptive capacity of power systems depends on their inherent structural characteristics. This asymmetry underscores a central challenge for European energy security—enhancing flexibility and reducing structural lock-in.

6. Conclusion

The results show that higher relative gas prices reduce its share in combined coal–gas generation, while higher carbon prices strengthen gas competitiveness and amplify substitution through interaction effects. Robustness checks confirm that these findings hold across alternative measures of relative price. Heterogeneity analysis reveals clear asymmetries: high gas-share and low coal lock-in countries respond more strongly to price and carbon signals, whereas during the crisis window, price effects remain stable but the marginal impact of carbon costs weakens. Overall, the findings highlight the critical role of short-term fuel substitution in ensuring energy security. Market signals remain the primary driver of coal–gas substitution, yet the effectiveness of policy instruments may diminish under crisis conditions, and structural lock-in undermines the resilience of power systems. Building on these insights, policy priorities should proceed in stages: in the near term, enhancing gas-fired flexibility and supplementing market signals with targeted supply security measures can provide a buffer against shocks; over the medium term, reducing coal dependence can ease structural rigidity and strengthen adaptability; and in the longer run, sustained renewable expansion and stronger policy transmission during crises will be essential to consolidate resilience.

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