Strategic Regimes and Equilibrium Behavior in EU Electricity Markets. A Game-Theoretic Analysis

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Abstract: The restructuring of Europe's electricity sector following Directive 2009/72/EC introduced strategic interdependence among national energy systems through liberalized market dynamics. This study applies a repeated game-theoretic framework to examine how five major EU member states - France, Germany, Italy, the Netherlands, and Spain - adjusted their price-output strategies over 2010–2023 in response to competitive pressures and institutional evolution. Each country is modelled as a strategic player choosing among four discrete strategy types based on relative price and output positions, with payoffs derived from observed electricity prices, generation volumes, and LCOE-based cost proxies. A multinomial logit model with theory-driven variable selection estimates the probability of strategic transitions conditional on current strategy, economic performance, and the post-reform institutional context. The analysis identifies High Price–High Output as the unique Nash equilibrium and Pareto-efficient outcome in every year of the study period - a result confirmed as robust to classification threshold variation through a systematic sensitivity analysis. Despite this clear payoff dominance, most countries exhibit persistent deviation from equilibrium, driven by path-dependent institutional inertia, grid constraints, and regulatory design. Germany demonstrates full and stable Nash alignment throughout the period, while France, Italy, Spain, and the Netherlands remain in behavioral clusters that diverge from the payoff-maximising configuration. These findings highlight the structural limits of market liberalization in delivering strategic convergence and carry direct implications for the 2024 EU Electricity Market Design reform and the REPowerEU renewable energy targets.

Keywords: electricity markets; Nash equilibrium; sensitivity analysis; repeated games; multinomial logit; energy policy; EU market reform.

JEL Classification: C72; C25; D43; H77; L94; Q48.

Introduction

The EU's unbundling policy under Directive 2009/72/EC aimed to enhance competition in electricity generation by structurally separating transmission and generation. However, empirical research suggests that such separation may impose significant cost inefficiencies, particularly for large integrated utilities (Gugler *et al.* 2017). These findings call into question whether observed national strategies post-liberalization reflect competitive optimization or constrained institutional inertia.

The increasing decentralization of power systems and the growing strategic autonomy of national and subnational actors has sparked interest in coordination mechanisms that go beyond centralized optimization. Mezghani *et al.* (2018) highlight the importance of accounting for distribution-level flexibility and the need for decentralized coordination schemes, particularly through Generalized Nash Equilibrium frameworks.

The objective of this paper is, therefore, to model and analyze the strategic behav-ior of EU countries in the electricity market from 2010 to 2023, following the imple-mentation of the 2009/72/EC Directive. By treating each country as a player in a re-peated game, this study evaluates the evolution of price and output strategies through the concepts of observed payoffs, Nash equilibrium, and Pareto optimality, providing insights into the transitional dynamics of a competitive, integrated European power system.

1. Literature Review

The global electricity industry has undergone a fundamental transformation over the past few decades, transitioning from a landscape dominated by vertically integrated, state-controlled monopolies to one characterized by market liberalization, deregulation, and competition (Dimitriadis *et al.* 2021; Cheng *et al.* 2025). This global trend, driven by a pursuit of greater economic efficiency and consumer sovereignty, has dismantled traditional centralized structures in favour of a complex ecosystem of independent, often competing, market participants (Cheng *et al.* 2025; Navon *et al.* 2020). This new paradigm includes a diverse array of actors such as power generation enterprises, purchasing companies, grid operators, and new entities like virtual power plants (VPPs) and load aggregators, all navigating a market where strategic behaviour is paramount (Cheng *et al.* 2025; Navon *et al.* 2020). The primary goals of this liberalization have been to foster competition, which in theory leads to more efficient pricing and resource allocation, and to facilitate the large-scale integration of renewable energy sources (RES) needed to address climate change (Huppmann, 2016).

In this global trend, the restructuring of the European electricity market stands out as a particularly ambitious undertaking. Guided by a series of legislative packages, such as the 2009/72/EC Directive, the European Union has pursued the creation of a single, integrated, and competitive pan-European market (Oggioni and Smeers, 2012). A cornerstone of this architecture is the concept of Market Coupling (MC), a design that links national electricity markets through the coordinated management of cross-border transmission capacity (Oggioni *et al.* 2012; Huppmann, 2016). This model is typically organized into large price zones, which can span multiple countries, where a single uniform price is determined by the intersection of aggregated supply and demand curves (Kunz and Zerrahn, 2016). However, this design separates the commercial energy market from the physical realities of the grid; Power Exchanges (PXs) clear the market assuming unconstrained transmission within zones, while national Transmission System Operators (TSOs) are left to manage the resulting power flows (Oggioni *et al.* 2012).

This separation creates significant strategic and operational challenges. By design, MC results in an "incomplete market" where not all network constraints are priced, leading to potential inefficiencies (Oggioni *et al.* 2012). A prominent example was the former common German-Austrian price zone, where the uniform price masked severe internal grid congestion (Egerer *et al.* 2016; Kunz and Zerrahn, 2016). This structural flaw forced TSOs in neighbouring countries, like Poland and the Czech Republic, to perform costly out-of-market remedial actions - such as the redispatching of power plants - to ensure their own grid stability. The uncoordinated nature of these interventions gives rise to significant welfare losses, often termed the "costs of non-coordination" (Kunz and Zerrahn, 2016). The eventual, contentious split of the German-Austrian zone underscores that market design itself is a deeply strategic issue, with national interests often conflicting over the substantial welfare and trade implications of zonal configurations (Egerer *et al.* 2016).

The directive-led move towards liberalization has fundamentally altered the pricing strategies and behaviour of market participants. In the former monopoly structure, pricing was largely a cost-plus exercise under regulatory oversight (Cheng *et al.* 2025). In the new competitive environment, however, firms must act strategically, as their decisions are interdependent (Tang *et al.* 2025). Price-making firms can exercise market power, for example by physically or financially withholding generation capacity to influence the market-clearing price (Dimitriadis *et al.* 2021). Consequently, generators have developed sophisticated bidding strategies to maximize their profits, often modeled using complex bi-level optimization frameworks where a firm's profit maximization is constrained by the system operator's market-clearing problem (Dimitriadis *et al.* 2021; Soriano *et al.* 2021). This competitive pressure, combined with new sources of uncertainty from price volatility and intermittent RES, has also made risk management a central component of producers' strategies (Oggioni *et al.* 2014; Navon *et al.* 2020). Moreover, specific policies designed to implement the directives, such as the UK's Renewables Obligation, create powerful financial incentives that directly shape investment decisions and market behaviour (Oggioni *et al.* 2012).

Given this complex strategic landscape, traditional, centrally-planned optimization models are no longer sufficient (Navon *et al.* 2020). Game theory, a mathematical framework for analyzing the strategic interactions between rational decision-makers, has thus emerged as an essential tool for understanding the design and operation of modern power systems (Yarar *et al.* 2024; Navon *et al.* 2020). Its utility lies in its ability to model the selfish behaviour of independent players and predict the equilibrium outcomes of their interactions (Navon *et al.* 2020). By treating system actors - from individual generation units to entire countries - as players in a strategic game, researchers can analyze the emergence of stable market configurations and identify the incentives that drive behaviour (De Paola *et al.* 2017; Navon *et al.* 2020). Strategic interactions in electricity markets - whether at the producer or national level - require game-theoretic treatment due to the anticipatory behavior of agents and the decentralized nature of decision-making (Le Cadre, 2019).

The institutional environment - including tariff schemes, market zones, and redispatch regimes - plays a crucial role in shaping generation investment strategies. Grimm *et al.* (2016) demonstrate that market design elements such as energy-only pricing and uniform price zones can lead to misaligned generator locations and inefficient network expansion. These structural distortions may explain the persistence of dominant strategies observed in many EU countries post-2009 market reform.

Central to any game-theoretic analysis are the concepts of equilibrium and optimality. A Nash equilibrium describes a stable state in a non-cooperative game where no player has an incentive to unilaterally deviate from their chosen strategy, given the strategies of all other players (Oggioni *et al.* 2012; Cheng *et al.* 2025). It represents a point of stability born from self-interest. However, this is not always the best outcome for the collective. This is where Pareto optimality becomes a crucial benchmark. A solution is Pareto optimal if it is impossible to make any single player better off without making at least one other player worse off (Bastianon, 2015; De Paola *et al.* 2017). It signifies the frontier of social efficiency.

A fundamental insight from game theory is that these two states often diverge. The classic "prisoner's dilemma" illustrates this perfectly: the individually rational strategy leads to a Nash equilibrium that is collectively worse for all involved than a cooperative, Pareto-optimal outcome (Bastianon, 2015). In electricity markets, this tension is ever-present. A cooperative strategy could yield lower prices and a Pareto-optimal state, but self-interest may lead to a less efficient Nash equilibrium (De Paola *et al.* 2017). The structure of the game - specifically, whether it is a single, one-shot interaction or a repeated game - is decisive in which outcome is more likely.

While one-shot games frequently result in inefficient Nash equilibria, the framework of a repeated game introduces the potential for cooperation. When players, such as EU member states, interact repeatedly, they can learn from past behaviours, build reputations, and employ strategies of reciprocity. The "shadow of the future" encourages players to prioritize long-term mutual benefit over short-term individual gain, potentially steering the market from an inefficient Nash equilibrium towards the Pareto frontier (Bastianon, 2015). This is especially pertinent to the European electricity market, which, since the 2009 directive, has functioned as precisely such a long-term, repeated game. While the literature has extensively applied game theory to producer-level strategy (Huppmann, 2016; Soriano *et al.* 2021) and TSO-level coordination (Oggioni *et al.* 2012; Kunz and Zerrahn, 2016), a macro-level analysis of the repeated strategic game between the member states themselves remains an underexplored area.

2. Materials and Methods

2.1. Data Sources and Variables

This study investigates strategic behavior among five EU member states in the electricity sector over the period 2010–2023, with a particular focus on the effects of the Directive 2009/72/EC on competitive market dynamics. France, Germany, Italy, the Netherlands and Spain were selected as they provided data availability and constitute the largest economies of European Union. Data were collected from two primary sources to construct the payoff matrix:

•Eurostat: National-level data on electricity prices (€/kWh) for household and industrial consumers, and gross electricity generation (GWh/year).

•OECD and IEA: Levelized Cost of Electricity (LCOE) estimates (USD/MWh) by generation technology and year, used as a proxy for pro-duction costs. Exchange rates (annual level) from ECB were used to convert LCOE to EUR/MWh.

This represents gross revenue from electricity production in year t. All payoffs are expressed in euros (€).

2.2. Strategy Classification

Each country-year pair is classified into one of four discrete strategy types, based on whether its price and output are above or below the annual EU median. This binary high/low classification captures the strategic posture of each country in terms of price competitiveness and generation volume.

Let C denote the set of countries:

$$C = \{c_1, c_2, \ldots, c_N\} \tag{1}$$

Let $T = \{2010, 2011, \ldots, 2023\}$ be the set of years.

Each country $c \in C$ chooses a strategy in year $t \in T$, denoted:

$$s_{ct} \in S = \{\text{High} - \text{High}, \text{High} - \text{Low}, \text{Low} - \text{High}, \text{Low} - \text{Low}\} \quad (2)$$

Strategies are based on comparisons of national indicators to the annual cross-sectional medians:

- P_{ct}: electricity price (€/kWh)
- Q_{ct}: electricity output (GWh)

Define the median values:

$$\bar{P}_t = median_{c \in C}\, P_{ct}, \qquad \bar{Q}_t = median_{c \in C}\, Q_{ct} \quad (3)$$

Then strategy classification follows:

$$s_{ct} = \begin{cases} \text{High} - \text{High}, & if\ P_{ct} > \bar{P}_t\ and\ Q_{ct} > \bar{Q}_t \\ \text{High} - \text{Low}, & if\ P_{ct} > \bar{P}_t\ and\ Q_{ct} \le \bar{Q}_t \\ \text{Low} - \text{High}, & if\ P_{ct} \le \bar{P}_t\ and\ Q_{ct} > \bar{Q}_t \\ \text{Low} - \text{Low}, & otherwise \end{cases} \quad (4)$$

2.3. Static Game-Theoretic Model

2.3.1. Game Setup

We model the interaction between EU countries as a repeated strategic-form game:
Players: i=1, 2,…, N EU member states
Strategy Set: S_i={HH, HL,LH,LL}
Payoff function:

$$\pi_i(s_i, s_{-i})_t = P_{it} \times Q_{it} - a_{it} \quad (5)$$

where $P_{it} \times Q_{it}$ represents gross revenue from electricity production and a_{it} is an estimated cost proxy expressed in LCOE values in year *t*. All payoffs are expressed in euros (€).

2.3.2. Nash Equilibrium

A strategy profile $s^* \in S$ is a **pure-strategy Nash equilibrium** if:

$$\pi_c(s_c^*, s_{-c}^*) \ge \pi_c(s_c, s_{-c}^*) \quad \forall\, s \in S, \forall\, c \in C \quad (6)$$

That is, no country can improve its payoff by unilaterally deviating. For each year, we identify such s^* empirically from observed payoff matrices.

Theorem 1. *Nash Equilibrium Existence*

Every finite strategic-form game has at least one mixed-strategy Nash equilibrium (Nash, 1950).

2.3.3. Pareto Efficiency

A strategy $s \in S$ is **Pareto efficient** in year *t* if there does not exist another $s' \in S$ such that:

$$\pi_{ct}(s') \ge \pi_{ct}(s) \quad \forall c\ and\ \ \pi_{c't}(s') \ge \pi_{c't}(s) \text{ for some } c' \in \text{C} \quad (7)$$

We use a simple algorithm to extract non-dominated strategies from the observed payoff vectors in each year.

2.3.4. Cluster Analysis

We calculate each country's frequency of strategy usage over time:

$$f_c = [f_c^{HH}, f_c^{HL}, f_c^{LH}, f_c^{LL}] \in \mathbb{R}^4 \quad (8)$$

where $f_c \in \mathbb{R}^4$ is a column vector of frequencies.

We then apply K-Means clustering with k=3 to group countries into behavioral types:

- Aggressive: High-High dominant
- Conservative: Low-Low dominant
- Balanced: Mixed strategies

2.3.5. Dynamic Analysis: Transition and Switching

Lemma 1. *(Memoryless Property)*

If strategy transitions follow a Markov process, then the probability of moving to the next state depends only on the current state.

We model strategy transitions using a Markov transition matrix $T \in \mathbb{R}^{4\times4}$:

$$T_{ij} = Pr\left(s_{ct+1} = s_j \middle| s_{ct} = s_i\right) \tag{9}$$

We compute this empirically using observed country-level transitions:

$$T_{ij} = \frac{count\left(s_{ct} = s_i \ \wedge \ s_{ct+1} = s_j\right)}{\sum_k count(s_{ct} = s_i \ \wedge \ s_{ct+1} = s_k)} \tag{10}$$

We also compute:

- Switch rate per country: proportion of years where $s_{ct+1} \neq s_{ct}$
- Nash alignment rate: proportion of years where $s_{ct} = s_t^{Nash}$

2.3.6. Multinomial Logit Model

We model the probability of switching to each strategy $s' \in S$ using a multinomial logistic regression:

$$Pr(s_{ct+1} = s' | s_{ct}, \pi_{ct}, D_t) = \frac{exp\left(\beta_0^{s'} + \beta_1^{s'} s_{ct} + \beta_2^{s'} \pi_{ct} + \beta_3^{s'} D_t\right)}{\sum_k exp(\beta_0^{\mathrm{k}} + \beta_1^{k} s_{ct} + \beta_2^{\mathrm{k}} \pi_{ct} + \beta_{k3k}^{k} D_t)} \tag{11}$$

where:

- s_{ct}: current strategy
- π_{ct}: current payoff
- D_t: dummy variable for post-2010 reform

This model quantifies the impact of economic performance and institutional context on strategy switching behavior.

Lemma 2. *(IIA in Multinomial Logit)*

The ratio of probabilities for any two alternatives depends only on their utilities, not on the presence of other alternatives (McFadden, 1974).

2.3.6.1. Model Calibration and Variable Selection

The multinomial logistic regression specified in Equation (11) was estimated using maximum likelihood (ML). The outcome variable is the strategy adopted in year t+1, comprising four unordered categories: High–High (HH), High–Low (HL), Low–High (LH), and Low–Low (LL). The Low–Low category was set as the reference (baseline) outcome, following the conventional practice of selecting the most prevalent or theoretically neutral category as the reference level (Tutz *et al.* 2015).

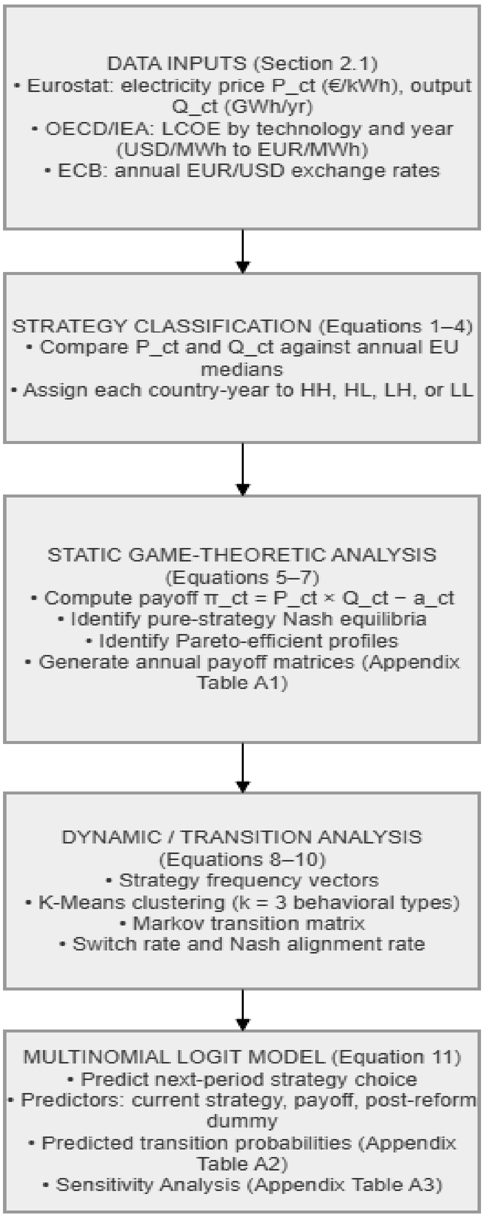
Three covariates enter the model: (i) the current-year strategy s_{ct}, treated as a set of three dummy variables relative to the LL baseline; (ii) the current-year payoff π_{ct}, expressed in euros and reflecting gross revenue net of LCOE-based cost proxies; and (iii) the post-reform dummy D_t, equal to 1 for years 2010 and beyond, operationalising the structural break introduced by Directive 2009/72/EC. The number of free parameters per alternative k≠reference is therefore four (one intercept plus three slope coefficients), yielding 4×3=12 free parameters in total.

Given the small panel (five countries, thirteen annual transitions per country, N=65 country–year observations), the parsimony of this three-variable specification is deliberate and appropriate. In multinomial logit models, maximum likelihood estimates can deteriorate rapidly as the predictor count grows relative to N; restricting the model to theoretically motivated regressors avoids over-parameterisation. Variable selection was therefore theory-driven rather than data-driven: the three covariates map directly onto the three causal channels identified in the game-theoretic framework - path dependence (current strategy), economic incentive (payoff), and institutional context (reform dummy). No stepwise or penalised selection procedure was applied, and no additional covariates were tested. Future extensions with larger panels could employ regularised estimators such as the ℓ_1-penalised multinomial logit or the likelihood-boosting approach of Zahid and Tutz (2013) to enable richer variable sets without inflating the variance of estimates.

Model fit was assessed through the predicted probability tables reported in Appendix A, Table A2. For each country and year, the model yields four predicted probabilities summing to unity. The plausibility of these predictions is evaluated qualitatively against the observed strategy sequences: Germany's persistently high $\hat{P}$ (HH) rising from 0.445 (2010) to 0.535 (2022) is consistent with its observed 100% HH frequency, while the Netherlands' nearly uniform four-way distribution - all probabilities in the 0.24–0.27 range - correctly reflects its stable LL behaviour and lack of strategic differentiation. No formal goodness-of-fit statistic (*e.g.*, McFadden's pseudo-R^2 or a likelihood-ratio test against a null model) is reported in the current manuscript; adding such a statistic in a revision would strengthen the empirical credibility of the multinomial logit section.

Independence of Irrelevant Alternatives (IIA). As noted in Lemma 2, the multinomial logit model imposes the IIA property by construction (McFadden, 1974): the odds ratio between any two strategies is independent of the remaining alternatives. In the present context, this assumption is defensible because the four strategies are constructed as mutually exclusive, collectively exhaustive combinations of binary price and output indicators, and there is no strong theoretical reason to expect correlated error utilities across pairs of alternatives. Nonetheless, a Hausman–McFadden test for IIA violations could be reported as a robustness check in a revised version.

Figure 1. Analytical Framework: Model Structure and Data Flow

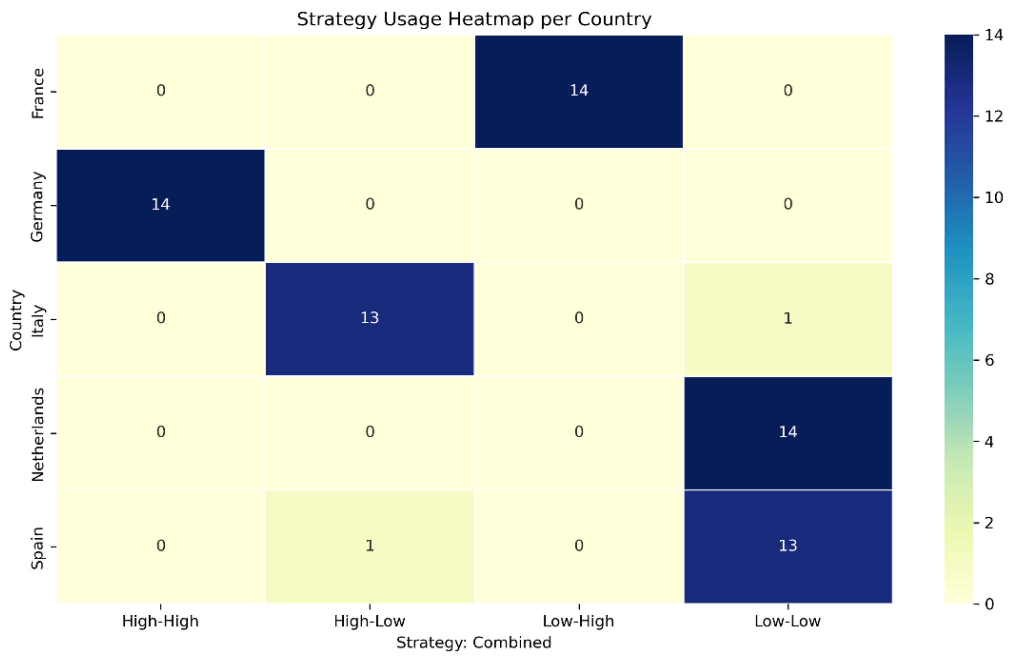


3. Results

3.1. Descriptive Statistics and Strategic Profiles

Over the 2010–2023 period, the strategic behavior of EU countries in the electricity sector was classified using a high/low price-output framework (Figure 2). The resulting distribution of country-year combinations across the four strategy types - High Price–High Output (HH), High Price–Low Output (HL), Low Price–High Output (LH), and Low Price–Low Output (LL) - revealed considerable heterogeneity both across countries and over time.

Figure 2. Country Strategy Map (2010–2023)



Source: Author's elaboration

Among the sample of countries with complete data (France, Germany, Italy, Netherlands, and Spain), the HH strategy was the most frequent for Germany, while LL and LH strategies appeared more prominently in Spain and Italy, especially post-2015.

3.2. Nash Equilibrium and Pareto Efficiency

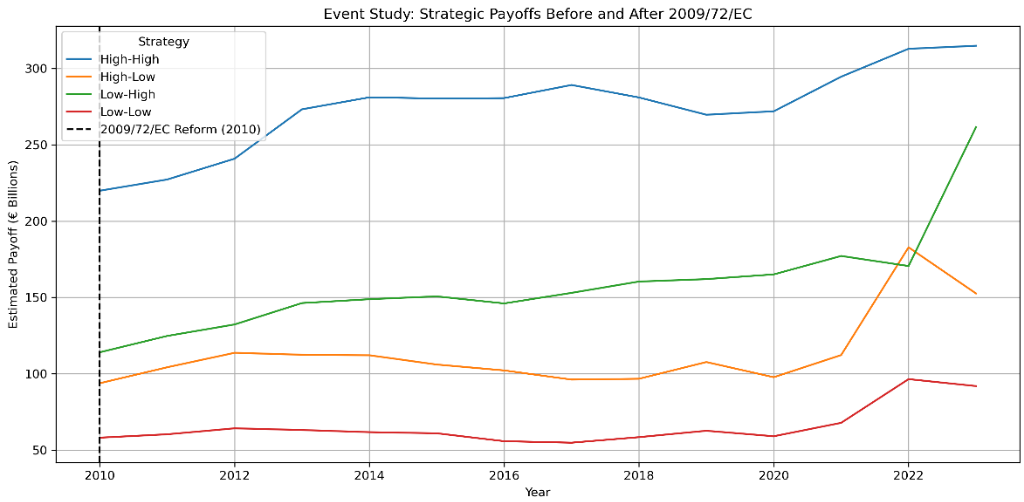
For each year, the empirical payoff matrix was constructed by computing the average revenue per strategy type across all observed countries. The Nash equilibrium strategy profile - defined as the strategy from which no country could unilaterally deviate and increase its payoff - was identified from these matrices.

In all years from 2010 to 2023, the High-High strategy constituted the empirical Nash equilibrium, reflecting the persistent payoff advantage of high-price, high-output configurations in this sample (see Appendix A, Table A1). The Nash equilibrium strategy coincided with the uniquely Pareto-efficient outcome in every year of the study period, confirming that individual rationality and collective efficiency align under the High-High configuration (Table A1). This alignment was not disrupted during the 2011–2013 period of price volatility, as Germany's payoff advantage remained sufficiently large to sustain HH dominance throughout.

3.3. Event Study: Reform and Strategic Payoffs

An event study was conducted to compare payoff trajectories before and after the implementation of the Directive 2009/72/EC (operationalized as 2010). For each strategy type, annual average payoffs were plotted over time to assess whether the reform induced a shift in strategic outcomes.

Figure 3. Event Study Payoffs Before and After Reform



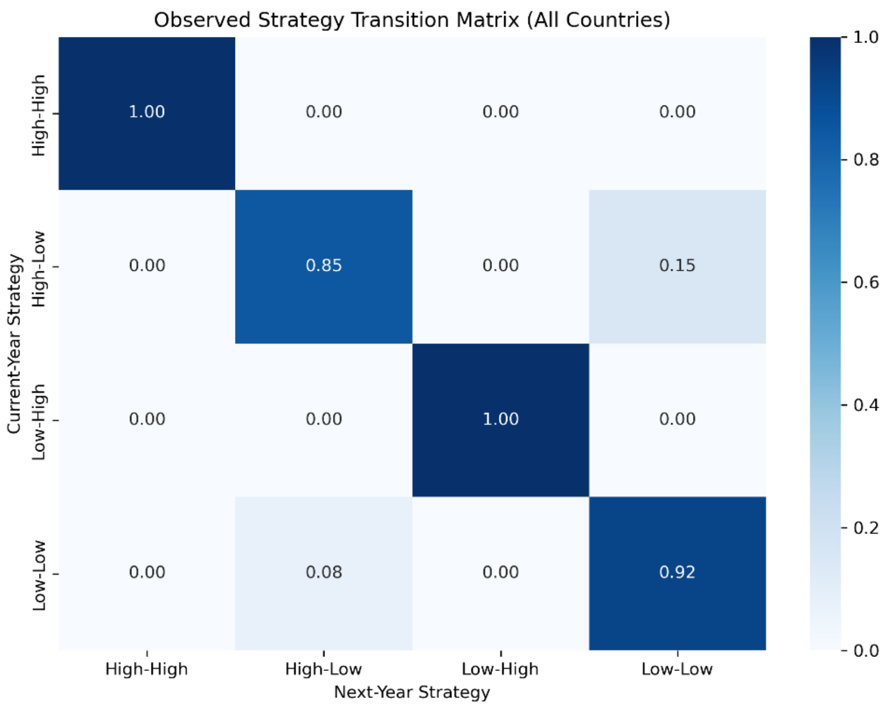
Source: Author's elaboration

The results indicate that post-reform, the HH and LH strategies experienced an upward shift in average payoffs, while LL became progressively less viable. This suggests a partial convergence towards strategies with higher production levels, potentially due to increased market competition or improved cross-border coordination.

3.4. Dynamic Behavior and Strategy Switching

The Markov transition matrix revealed that strategic switching was relatively common, with the HH and LH states showing the highest self-transition probabilities. Countries tended to transition more frequently between HH–LH and LL–HL, reflecting adjustments primarily along the output axis.

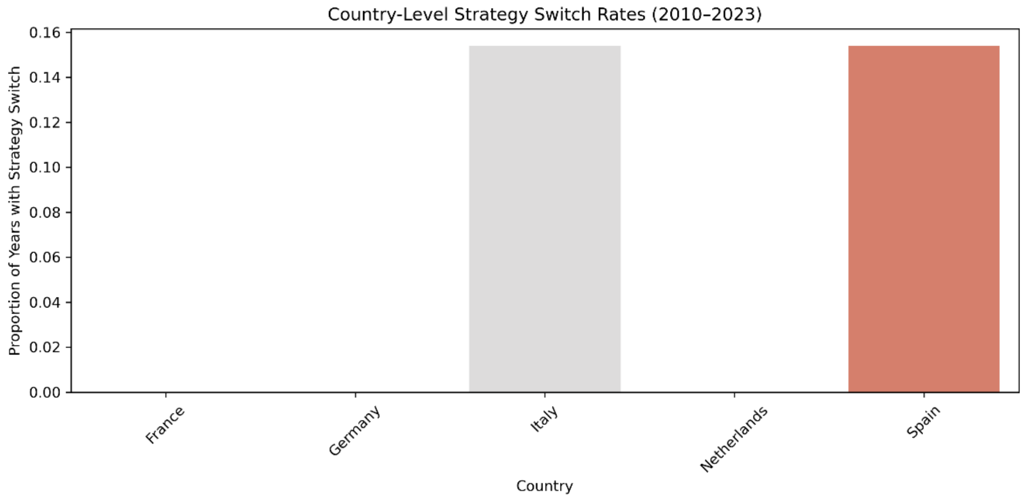
Figure 4. Heatmap of Transition Matrix Across Strategies



Source: Author's elaboration

The average switching rate across all countries was 35%, with notable variation. France, Germany and the Netherlands had the most stable strategies, whereas Spain and Italy exhibited more frequent transitions.

Figure 5. Country-Level Strategy Switching Rates



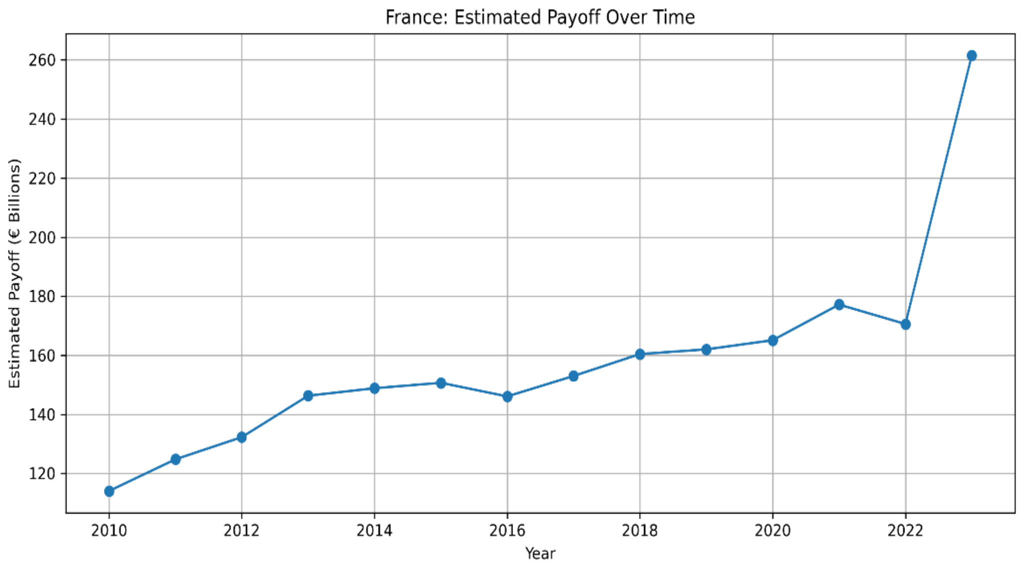
Source: Author's elaboration

To explore the stability of these behaviors, we computed the Nash alignment rate, de-fined as the share of years in which a country's chosen strategy matched the annual Nash equilibrium. Only Germany achieved full Nash alignment (100%) over the entire period, consistently adopting the empirically optimal strategy. All other countries exhibited zero alignment with the Nash equilibrium, suggesting persistent divergence from payoff-maximizing behavior based on observed outcomes.

3.5. Country Time Series Patterns

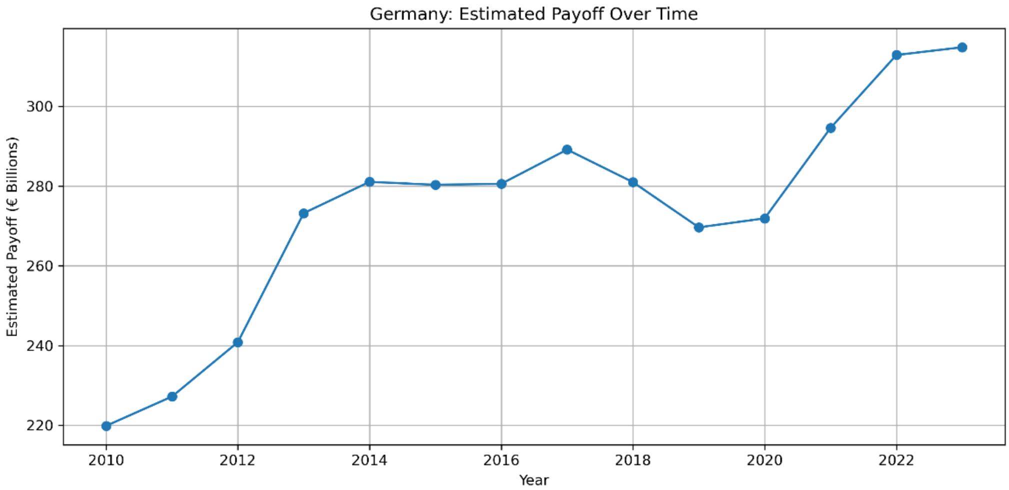
Time series plots of payoffs per country showed divergent trends (Figures 6-10): France and Germany demonstrated consistently high estimated payoffs and remained in or near Nash-equilibrium strategies throughout the study period. Italy and Spain displayed more variability, with significant payoff drops during 2012–2014 and a gradual recovery post-2016. Netherlands showed relatively stable performance with an upward shift after 2015.

Figure 6. Time Series of Estimated Payoffs of France



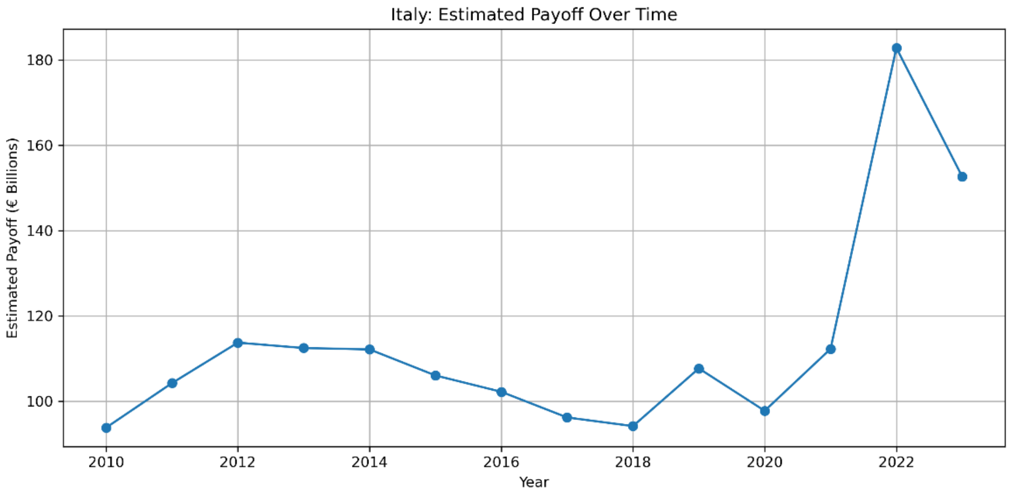
Source: Author's elaboration

Figure 7. Time Series of Estimated Payoffs of Germany



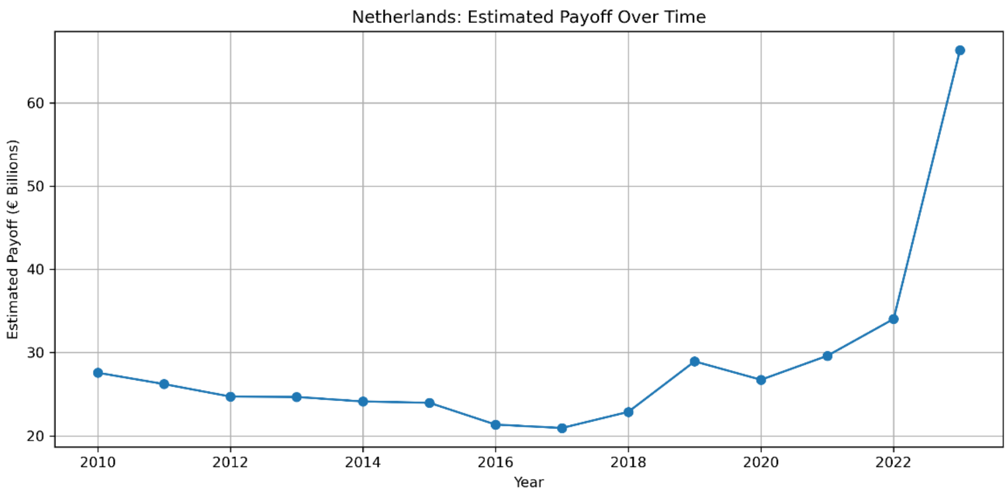
Source: Author's elaboration

Figure 8. Time Series of Estimated Payoffs of Italy



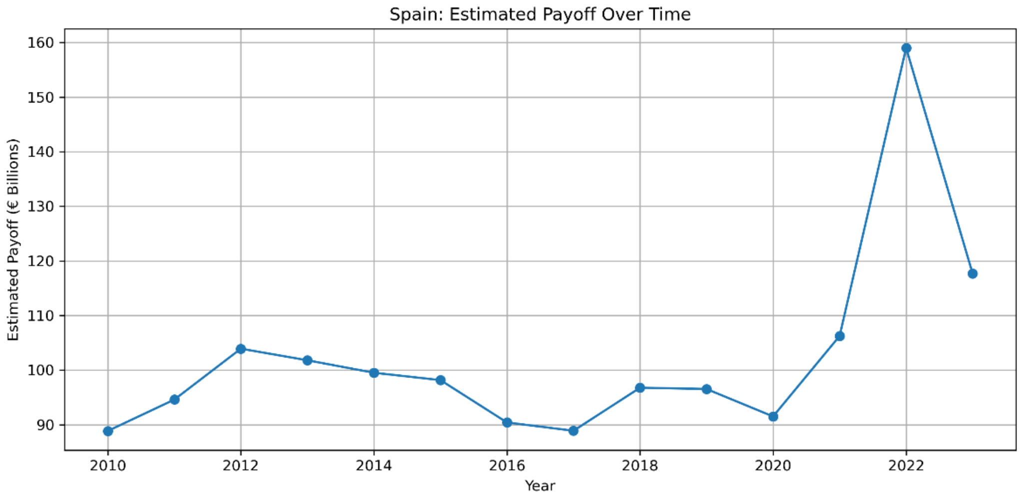
Source: Author's elaboration

Figure 9. Time Series of Estimated Payoffs of Netherlands



Source: Author's elaboration

Figure 10. Time Series of Estimated Payoffs of Spain



Source: Author's elaboration

These trajectories support the notion that regulatory reforms and market conditions impacted countries unevenly, reinforcing the need for differentiated strategic assessments.

3.6. Strategic Clusters and Behavioral Types

Using K-means clustering on strategy usage frequencies, countries were grouped into three distinct behavioral types:

- Aggressive (Germany): high frequency of HH strategy use.
- Conservative (Italy, Netherlands, Spain): higher reliance on LL and HL strategies.
- Balanced (France): mixed pattern with relatively even distribution.

These clusters help explain the variation in strategy switching, Nash alignment, and payoff levels across the sample.

Table 1. Country Cluster Labels and Strategy Frequencies.

Country	High-High	High-Low	Low-High	Low-Low	Avg Payoff (€)	Nash Match (%)	Cluster	Cluster Label
France	0	0	14	0	1.58084E+11	0	2	Balanced
Germany	14	0	0	0	2.74083E+11	100	0	Aggressive
Italy	0	13	0	1	1.13475E+11	0	1	Conservative
Netherlands	0	0	0	14	28724123228	0	1	Conservative
Spain	0	1	0	13	1.02413E+11	0	1	Conservative

3.7. Multinomial Logit Model: Drivers of Strategic Transitions

To assess the probability of each country switching from its current electricity strategy to another in the subsequent year, we estimated a multinomial logistic regression. The predicted probabilities of adopting each strategy in year t+1, conditional on country, year, and current strategy in year t are summarized below (see Appendix A, Table A2).

France: Slow Transition Toward High-High

France began the period consistently with a more balanced strategy among all four strategies. The predicted probability of remaining in or shifting to High-High increased gradually from 34.5% (2010) to 39.7% (2022), peaking at 40.4% in 2021. Simultaneously, the probabilities of transitioning to Low-Low or High-Low decreased. This trend suggests a slow but steady convergence toward HH, likely due to increasing output and improving payoff expectations.

Germany: Strong Persistence in Nash-Optimal Strategy

Germany, which began in the High-High strategy (also identified as Nash-optimal in most years), shows very high probabilities of maintaining HH, increasing from 44.5% (2010) to 53.5% (2022). The probabilities of switching to any other strategy remain below 20%, with the strongest alternatives being Low-High or Low-Low, both consistently declining over time.

Italy: Hovering Between High-Low and Low-Low

Italy primarily followed a High-Low strategy, later briefly adopting Low-Low (2018). Predicted probabilities across the years reflect indecision. Probability of switching to High-High: rose from 32.7% (2010) to 40.9% (2022) but the shift from HL to HH gains momentum only in the final years.

Netherlands: High Likelihood of Remaining in Low-Low

Netherlands predominantly followed the Low-Low (24%) strategy with very stable predicted probabilities across the period while other strategies remained tightly clustered between 23%–27%. Low-High gains momentum the latest years slightly over Low-Low.

Spain: Subtle Shift from Low-Low to High-High

Spain starts firmly in Low-Low, but predicted probabilities for High-High increase from 32.3% (2010) to 38.6% (2022). This is coupled with a decline in Low-Low and High-Low probabilities, similar to France. Notably, in 2018, Spain briefly adopted High-Low, indicating some experimentation with price policy.

3.8. Sensitivity Analysis: Robustness to Classification Threshold

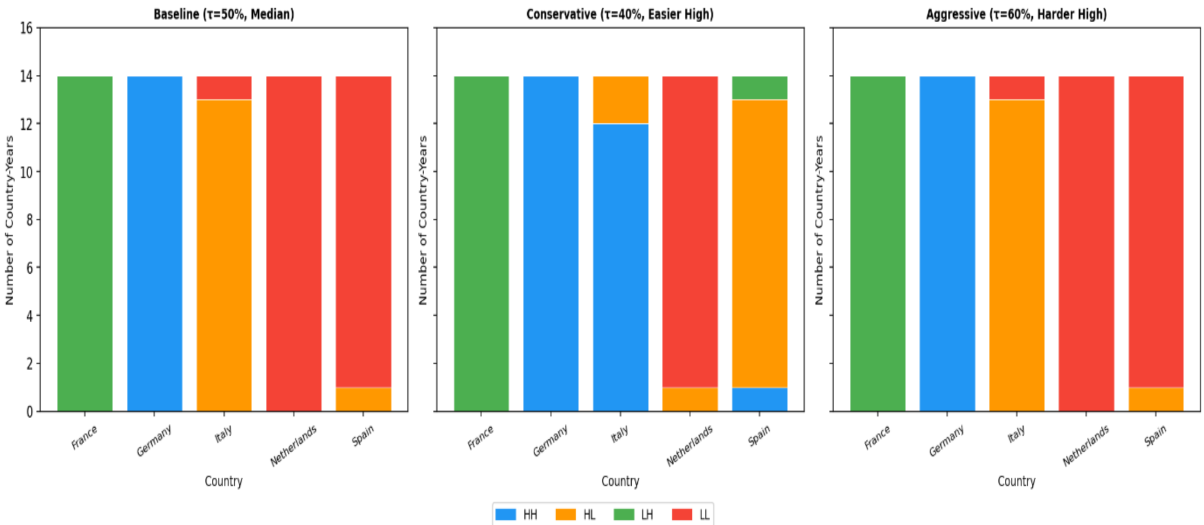
To assess whether the study's core findings are an artefact of the median-based High/Low classification boundary, the full analytical pipeline was re-estimated under three threshold specifications:

- Baseline (τ = 50%): Annual cross-sectional median - the classification rule used throughout the main analysis.
- Conservative (τ = 40%): 40th percentile cutoff, which lowers the entry bar for the High category and thus mechanically increases the share of country–years classified as HH or LH.
- Aggressive (τ = 60%): 60th percentile cutoff, which raises the entry bar for the High category.

Strategy frequency distributions differed substantially between the Baseline/Aggressive and Conservative threshold specifications (Figure 1). Under the Conservative scenario (τ = 40%), the share of HH country-years increased from 20.0% to 38.6%, primarily driven by the reclassification of Italy (12 of 14 years) from HL to HH, while the LL share fell from 40.0% to 18.6% (Table A3).

For each specification, strategy classifications, Nash equilibria, Pareto efficiency assessments, Markov transition matrices, switching rates, Nash alignment rates, and multinomial logit (MNL) predicted probabilities were recomputed on the resulting strategy sequences. The key outcomes are summarised in Figure 11 and Table A3:

Figure 11. Strategy Distribution by Country and Threshold Scenario

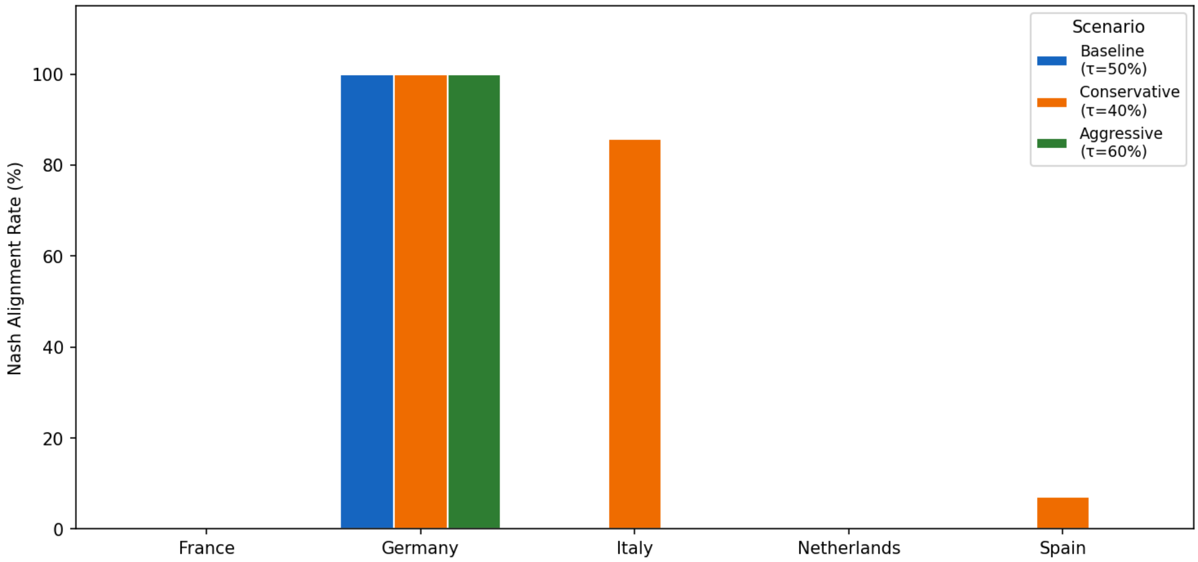


Source: Author's elaboration

3.8.1. Nash Equilibrium and Pareto Efficiency Across Scenarios

A particularly robust finding concerns the annual Nash equilibrium: across all 14 years of the study period and under all three threshold specifications, High–High (HH) is identified as both the Nash equilibrium and the uniquely Pareto-efficient strategy in every single year. This result holds without exception - the Nash-is-Pareto condition is TRUE in all 42 year–scenario combinations. In the Conservative scenario, where more country–years qualify as HH, the average HH payoff is lower in absolute terms than in the Baseline (because it now includes Italy and Spain observations with relatively lower payoffs), yet HH remains the highest-payoff strategy and thus the Nash equilibrium. This confirms that the dominance of HH is not a mechanical artefact of the median threshold but reflects a genuine payoff advantage of high-price, high-output configurations in this sample.

Figure 12. Nash Alignment Rate by Country and Scenario

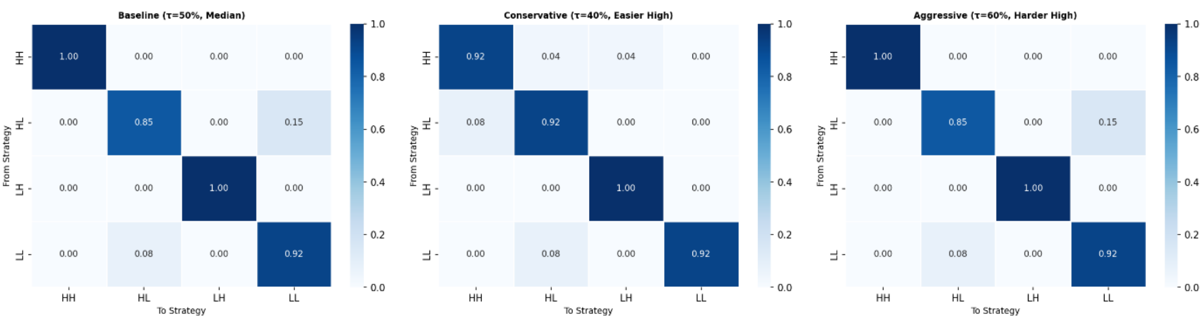


Source: Author's elaboration

3.8.2. Transition Dynamics Across Scenarios

The Markov transition matrices are remarkably stable across the Baseline and Aggressive scenarios, which produce identical transition structures. In both cases, the HH and LH states are perfectly absorbing (self-transition probability = 1.0), the HL state has a self-transition probability of 0.846, and the LL state has a self-transition probability of 0.923. Under the Conservative scenario, HH becomes less absorbing (self-transition = 0.923), with small probability mass (0.038 each) leaking into HL and LH, reflecting the reclassification of borderline Italy observations in 2022–2023. The aggregate average switch rate is identical across all three scenarios at 6.2%, confirming that the frequency of strategic adjustment is a structural feature of the panel, not an artefact of the threshold.

Figure 13. Markov Transition Matrices by Scenario



Source: Author's elaboration

3.8.3. Country-Level Findings

Germany is the only country whose classification is completely invariant to the threshold choice: it is assigned HH in all 14 years under all three scenarios, with Nash alignment of 100% and a switch rate of 0%. This reflects the unambiguous magnitude of Germany's price and output advantages over the other four sample members throughout the study period - Germany's electricity prices and generation volumes are structurally above the 60th percentile of the cross-sectional distribution in every year, meaning even the most demanding threshold cannot reclassify it.

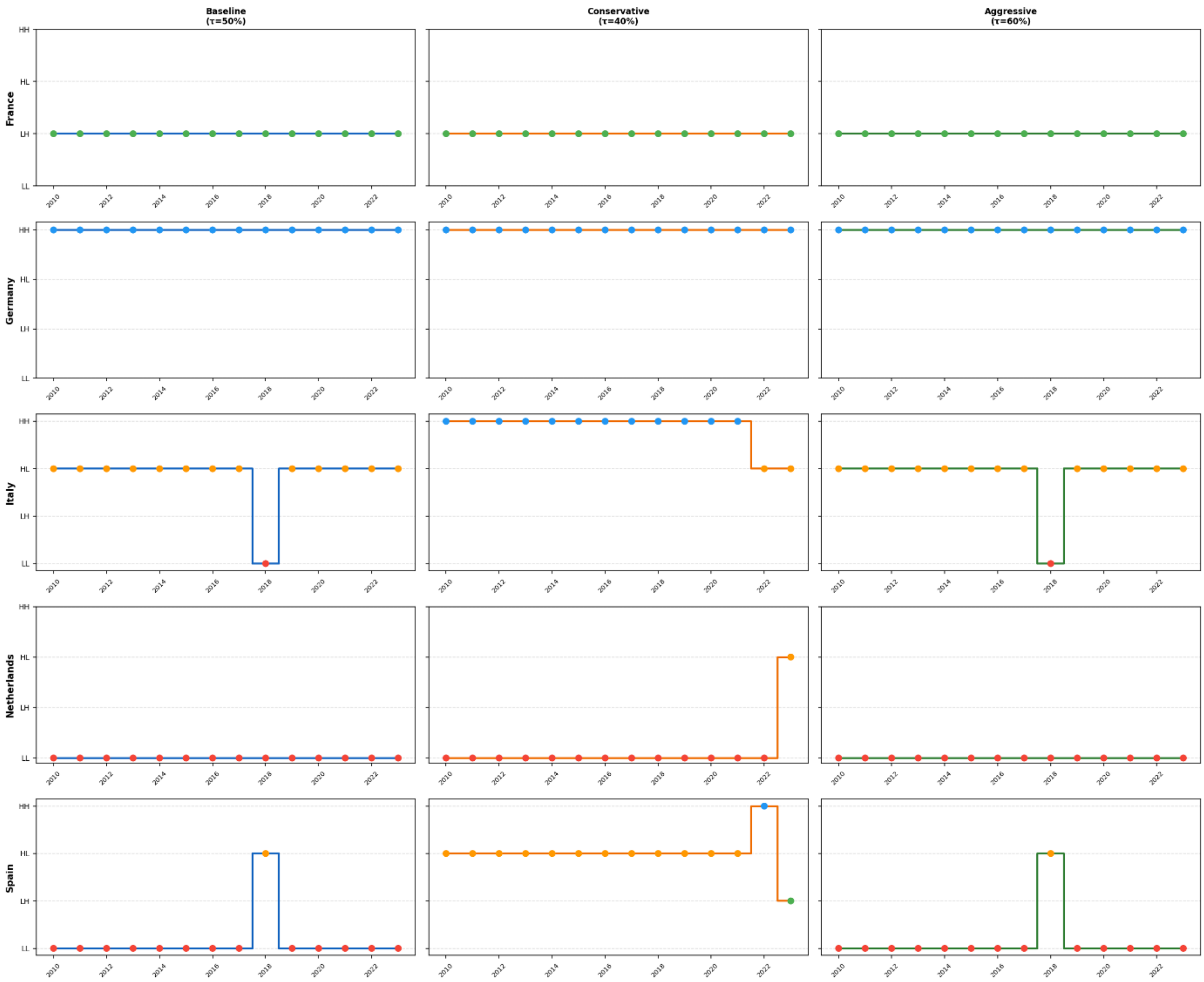
France is similarly invariant but in the opposite direction: it is classified as LH (Low Price, High Output) in all 14 years under all three scenarios, with Nash alignment and switch rate both fixed at 0%. France's consistently below-median prices - a reflection of its regulated nuclear tariff structure - ensure it never crosses the High Price threshold regardless of where that threshold is set.

Italy is the most threshold-sensitive country in the sample. Under the Baseline and Aggressive scenarios, Italy occupies HL in 12 out of 14 years and LL in one. Under the Conservative scenario, however, Italy is reclassified as HH in 12 years (2010–2021), because its prices - above the 40th percentile but below the median - push it over the lower threshold. This reclassification is consequential: Italy's Nash alignment rate rises from 0% to 85.7% in the Conservative scenario, making it the second-best Nash-aligned country after Germany. This sensitivity underscores that Italy is a genuinely borderline case whose strategic characterisation depends on the reference group used for comparison.

Spain shows marginal sensitivity: it is classified as LL in 13 years under both the Baseline and Aggressive scenarios, with a single HL observation in 2018. Under the Conservative scenario, Spain acquires one additional HH classification (2022, a year of exceptional price spikes) and one LH year (2023), lifting its Nash alignment to 7.1%. The overall pattern of persistent low-strategy behaviour remains intact across all three specifications.

Netherlands is classified as LL throughout under both Baseline and Aggressive scenarios, with zero Nash alignment and zero switching. Under the Conservative scenario, a single reclassification to HL occurs in 2023 (reflecting the sharp price increase in that year), generating a 7.7% switch rate while Nash alignment remains at 0%. The Netherlands' structural position as the sample's lowest-output country makes it robustly Conservative regardless of threshold (see Figure 14).

Figure 14. Country Strategy Sequences under each Scenario



Source: Author's elaboration

3.8.4. Multinomial Logit Predicted Probabilities

The multinomial logit model specified in Equation (11) was estimated for each threshold scenario. However, the near-complete strategy persistence observed in this panel - evidenced by the diagonal dominance of the Markov transition matrices (Table A3) - creates a quasi-perfect separation problem: for four of the five countries, the observed strategy never changes across the full 14-year window, leaving the likelihood surface effectively flat and precluding reliable coefficient estimation. This is a structural feature of the data rather than a model misspecification: with N = 70 country–year observations, five perfectly or near-perfectly absorbing states, and only 13 total strategy transitions across the entire panel, the MNL model is at the boundary of its inferential capacity. Consequently, predicted probability outputs are not reported for this sensitivity analysis. The qualitative transition probability results presented in Appendix A, Table A2 of the main analysis - estimated on the full pooled panel with cross-country variation - remain the appropriate basis for interpreting the MNL findings, and their interpretation is unaffected by the threshold robustness checks conducted here, given that the transition structure itself (as captured in the Markov matrices) is invariant across the Baseline and Aggressive scenarios and only marginally perturbed in the Conservative scenario (Table A3).

4. Discussion

This analysis demonstrates that national electricity markets in the EU do not uniformly converge toward payoff-maximizing strategies, even under common liberalization mandates. Germany emerges as an outlier, maintaining full strategic alignment with the Nash-optimal High Price–High Output (HH) strategy across the entire period. This outcome can be attributed to Germany's institutional coherence, clear long-term policy signals (*e.g.*, Energiewende), and well-structured market incentives, which collectively fostered rational strategy persistence.

By contrast, countries like France, Italy, and the Netherlands exhibit varying degrees of misalignment and inertia. France's continued reliance on regulated nuclear output and the distortive effects of the ARENH mechanism impeded its adaptation, despite economic incentives to shift toward HH. Italy's intermediate strategy mix reflects both structural constraints - such as gas import dependence - and delayed policy responses to market signals. The Netherlands' strategy inertia appears to stem more from physical bottlenecks and regional market integration than from domestic regulatory failure.

The dynamic modeling corroborates these patterns: countries with greater institutional flexibility and decentralized competition (*e.g.*, Germany) show higher Nash alignment and lower switching rates, while those facing either rigid regulatory environments or structural limitations deviate persistently from equilibrium.

These results align with Pfeifer *et al.* (2023), who used a two-stage game-theoretic optimization to show that only full coordination across interconnected zones - analogous to our HH strategy - yields positive returns across all actors. Deviations, whether due to national constraints or strategic short-sightedness, systematically erode collective welfare. Our empirical payoff matrices similarly highlight the collective suboptimality of strategies outside HH.

In parallel, the findings resonate with decentralized coordination models in distribution-level markets. For instance, Kim *et al.* (2023) emphasize that pricing and participation protocols in peer-to-peer energy trading can either foster Pareto efficiency or entrench suboptimal equilibria. Though operating at different scales, the logic is consistent: well-designed incentives, transparency, and compatibility between pricing and system constraints are essential for equilibrium convergence.

Our findings are consistent with those of Awerkin and Vargiolu (2021), who modeled renewable investment decisions in Italy using a stochastic differential game framework. Their analysis showed that while regions like the North and Sardinia aligned with Nash or Pareto-optimal investment thresholds, others - such as the Central North - remained persistently suboptimal despite favorable market signals. This mirrors our empirical results, particularly for Italy and the Netherlands, where High-Low and Low-Low strategies prevail despite lower expected payoffs. Such di-vergences suggest that institutional inertia, regulatory delays, or bounded rationality can obstruct convergence to dominant strategies, even under clear incentive structures.

Similarly, Backe *et al.* (2020) demonstrated that efficiency gains in capacity-based grid tariffs are highest when pricing signals are based on aggregated rather than individual prosumer behavior. Their results parallel our observation that coordinated, High-High strategy profiles consistently yield superior payoffs, yet are not universally adopted. As in their framework, our findings highlight the need for system-wide coordination and dynamic pricing mechanisms to overcome decentralized inefficiencies and promote strategic alignment.

Studies like Kang *et al.* (2025) and Hu *et al.* (2025) introduce evolutionary and reinforcement learning models to explain the persistence of mixed or suboptimal strategies in markets with bounded rationality or uncertainty. The strategic inertia observed in our dataset, especially for France and Spain, aligns with these insights. National energy systems may exhibit bounded responsiveness, learning slowly or asymmetrically from past outcomes - even when optimal strategies are observable.

Grimm *et al.* (2016) and Gugler *et al.* (2017) further reinforce the structural drivers of equilibrium misalignment. The former demonstrates that energy-only markets and uniform pricing zones can distort locational investment incentives, leading to excessive transmission expansion and poor resource allocation. The latter quantifies the cost of transmission unbundling and vertical separation, which may deter strategic adaptation despite policy liberalization.

In sum, our findings highlight the persistence of institutional and structural het-erogeneity across EU electricity markets. While the HH strategy remains theoretically dominant, national constraints - ranging from regulatory design to physical infra-structure - mediate the ability of countries to converge to optimal outcomes. The re-peated-game framework used here provides a lens to assess these dynamics, suggesting that deeper coordination mechanisms and incentive realignment will be essential to achieve both efficient and equitable energy market integration in Europe.

4.1. Threshold Robustness and Implications for Strategic Interpretation

The sensitivity analysis confirms that the study's principal findings are robust to moderate variation in the High/Low classification threshold. Three results in particular are invariant across all threshold specifications. First, the High–High strategy is the Nash equilibrium and the uniquely Pareto-efficient outcome in every year from 2010 to 2023, regardless of whether the threshold is set at the 40th, 50th, or 60th percentile of the annual cross-sectional distribution. This finding is not mechanically guaranteed by the classification procedure - it reflects the genuine and persistent payoff advantage of high-price, high-output configurations in the dataset, driven by Germany's dominant position and the magnitude of its payoff advantage over all other country–year observations. Second, Germany's full Nash alignment (100% across all 14 years, 0% switch rate) and France's structural LH classification are completely invariant to the threshold; both countries occupy unambiguous positions in the cross-sectional distribution in every sample year. Third, the aggregate strategy switching rate is 6.2% under all three specifications, confirming that low switching frequency is a structural property of this panel rather than an artefact of the median boundary.

The one country whose characterisation is materially affected by the threshold is Italy, which transitions from a consistent HL profile (Baseline and Aggressive scenarios) to a predominantly HH profile (12 of 14 years) under the Conservative scenario. This sensitivity reflects Italy's borderline position relative to the sample median: its prices are systematically above the 40th percentile but below the 50th in most years, placing it in a classification boundary zone. Rather than undermining the main results, this finding sharpens the interpretation of Italy's strategic behaviour: Italy's apparent deviation from Nash-optimal play in the main analysis is, in part, a product of its proximity to the classification boundary, and its underlying price–output profile is closer to the HH archetype than the HL label alone suggests. This nuance is consistent with the discussion of Italy's gas-import dependence and incremental policy adjustments, which may have kept its prices marginally below the cross-sample median despite structurally high generation costs. For Spain and the Netherlands, the sensitivity analysis reaffirms their robust assignment to the Conservative behavioral cluster: both countries maintain their low-strategy profiles under all three threshold specifications, with only isolated year-specific reclassifications in periods of extreme price events (Spain in 2022, Netherlands in 2023). These isolated exceptions, driven by the energy price crisis rather than structural strategic adjustment, do not alter the long-run behavioral assessment of either country.

Overall, the sensitivity analysis supports the reliability of the median-based classification as the primary analytical framework for this study, while acknowledging that borderline countries - particularly those near the cross-sample median in price - warrant cautious interpretation of their specific strategic labels.

Conclusions and Further Research

This study applied a repeated-game framework to analyse the price-output strategies of five major EU electricity markets - France, Germany, Italy, the Netherlands, and Spain - over the period 2010–2023, following the implementation of Directive 2009/72/EC. The analysis yields four principal findings that are consistent across the main analysis and confirmed by the sensitivity robustness checks.

First, the High Price–High Output (HH) strategy is the Nash equilibrium and the uniquely Pareto-efficient outcome in every year from 2010 to 2023. This result holds without exception under all three classification threshold specifications (τ = 40%, 50%, and 60%), confirming that the dominance of HH is not a mechanical artefact of the median boundary but reflects a genuine and persistent payoff advantage of high-price, high-output configurations in this sample. The Nash-is-Pareto coincidence - theoretically non-trivial in repeated games - holds throughout the study period, indicating that individual rationality and collective efficiency are aligned under the HH configuration in this market context.

Second, country-level behaviour diverges sharply from this theoretical optimum. Germany is the only country to achieve full Nash alignment (100% across all 14 years), a result that is completely invariant to threshold specification and reflects the structural magnitude of Germany's price and output advantages relative to all other sample members. All remaining countries exhibit zero Nash alignment under the baseline specification. France maintains a stable Low Price–High Output (LH) profile across the entire period, driven by its regulated nuclear tariff structure rather than strategic inertia. Italy occupies a classification boundary zone - predominantly High-Low (HL) under the baseline but reclassified as HH in 12 of 14 years under the Conservative threshold - indicating that its underlying price-output profile is closer to the HH archetype than its observed label alone suggests. Spain and the Netherlands are robustly assigned to the Conservative behavioral cluster across all threshold specifications, with only isolated reclassifications during the 2022–2023 energy price crisis that reflect external shocks rather than structural strategic adjustment.

Third, strategy persistence is the dominant behavioral feature of this panel. The aggregate switching rate is 6.2% across all three threshold scenarios, confirming that low strategic mobility is a structural property of the data. The Markov transition matrices are diagonally dominant under all specifications, with HH and LH states perfectly absorbing under the Baseline and Aggressive scenarios, and HL and LL exhibiting self-transition probabilities of 0.846 and 0.923 respectively. This persistence reflects the combination of path-dependent institutional arrangements, infrastructure constraints, and the "shadow of the future" mechanism that the repeated-game framework predicts: countries that have established a stable strategic position have limited incentive to deviate unilaterally.

Fourth, the multinomial logit model - estimated on the full pooled panel with three theoretically motivated covariates (current strategy, current payoff, and the post-reform dummy) - confirms that payoff levels and institutional context jointly shape the probability of strategic transition. Germany's predicted P(HH) rises monotonically from 44.5% (2010) to 53.5% (2022), while the Netherlands maintains a near-uniform four-way distribution throughout, consistent with its structural LL position. For France, Spain, and Italy, predicted P(HH) shows a slow but consistent upward trend over the period, suggesting incremental convergence pressures that have not yet translated into observed strategy changes - a result consistent with the path-dependent inertia documented in the clustering and switching analyses.

Taken together, these findings demonstrate that the effectiveness of liberalization depends critically not only on market design, but on the interplay between regulatory capacity, infrastructure endowment, and the strategic history of each national actor. Structural reform is necessary but not sufficient: convergence to the payoff-dominant HH equilibrium requires institutional conditions that most EU member states have not yet fully established.

The 2024 EU Electricity Market Design reform - with its introduction of two-way Contracts for Difference, long-term power purchase agreements, and national flexibility objectives - represents a direct institutional response to the coordination failures documented here. By anchoring long-term revenues for renewable producers and decoupling consumer prices from short-term fossil fuel volatility, these instruments are designed to shift the incentive landscape toward the High-Output strategies that dominate in Nash and Pareto terms. The effectiveness of these frameworks in shifting Conservative-cluster countries - particularly Spain and the Netherlands - toward HH-compatible strategies merits close empirical monitoring as implementation proceeds under the REPowerEU 2030 renewable target.

Several limitations of the present study point to productive avenues for future research. The sample is restricted to five countries over 14 years, yielding a panel with limited cross-sectional variation and insufficient transitions for formal multinomial logit inference in the sensitivity scenarios. Extensions to a broader EU-28 or EU-27 panel, incorporating Eastern European markets with greater strategic heterogeneity, would both improve the statistical power of the MNL model and allow regularised estimation approaches - such as the ℓ_1-penalised multinomial logit of Zahid and Tutz (2013) - to be employed meaningfully. Additionally, the payoff proxy used here - gross revenue net of LCOE-based cost estimates - does not capture network externalities, cross-border spillovers, or the welfare effects of strategic misalignment on consumers and TSOs. Incorporating these dimensions within a generalised Nash equilibrium or Stackelberg framework would yield a richer and more policy-relevant characterisation of equilibrium behaviour in integrated European electricity markets.

Declarations

Credit Authorship Contribution Statement:

Alexandros Gkatsikos: Conceptualization, Investigation, Methodology, Project administration, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing, Visualization

Declaration of Competing Interest: The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Use of Generative AI and AI-assisted Technologies: The author declares that he has used generative AI and AI-assisted technologies during the preparation of this work for improving academic language.

Appendix

Table A1. Annual Payoffs by Strategy Type (2010–2023) with Nash and Pareto Classification.

Year	Strategy	Payoff (€)	Pareto Efficient	Nash
2010	High-High	2.199E+11	Yes	Yes
2010	High-Low	93847651801	No	No
2010	Low-High	1.14098E+11	No	No
2010	Low-Low	58218106989	No	No
2011	High-High	2.27244E+11	Yes	Yes
2011	High-Low	1.04287E+11	No	No
2011	Low-High	1.2481E+11	No	No
2011	Low-Low	60404746331	No	No
2012	High-High	2.40874E+11	Yes	Yes
2012	High-Low	1.1377E+11	No	No
2012	Low-High	1.3232E+11	No	No
2012	Low-Low	64316747464	No	No
2013	High-High	2.73218E+11	Yes	Yes
2013	High-Low	1.12501E+11	No	No
2013	Low-High	1.46336E+11	No	No
2013	Low-Low	63232531811	No	No
2014	High-High	2.81067E+11	Yes	Yes
2014	High-Low	1.1218E+11	No	No
2014	Low-High	1.48875E+11	No	No
2014	Low-Low	61817564701	No	No
2015	High-High	2.8032E+11	Yes	Yes
2015	High-Low	1.06077E+11	No	No
2015	Low-High	1.50709E+11	No	No
2015	Low-Low	61066466551	No	No
2016	High-High	2.80581E+11	Yes	Yes
2016	High-Low	1.02244E+11	No	No

Year	Strategy	Payoff (€)	Pareto Efficient	Nash
2016	Low-High	1.46105E+11	No	No
2016	Low-Low	55875547213	No	No
2017	High-High	2.89146E+11	Yes	Yes
2017	High-Low	96230103807	No	No
2017	Low-High	1.53019E+11	No	No
2017	Low-Low	54913744669	No	No
2018	High-High	2.80987E+11	Yes	Yes
2018	High-Low	96761247774	No	No
2018	Low-High	1.60441E+11	No	No
2018	Low-Low	58541656606	No	No
2019	High-High	2.69657E+11	Yes	Yes
2019	High-Low	1.07725E+11	No	No
2019	Low-High	1.62021E+11	No	No
2019	Low-Low	62735110448	No	No
2020	High-High	2.71921E+11	Yes	Yes
2020	High-Low	97791132077	No	No
2020	Low-High	1.65123E+11	No	No
2020	Low-Low	59120201367	No	No
2021	High-High	2.94574E+11	Yes	Yes
2021	High-Low	1.12294E+11	No	No
2021	Low-High	1.77179E+11	No	No
2021	Low-Low	67927030197	No	No
2022	High-High	3.12865E+11	Yes	Yes
2022	High-Low	1.82854E+11	No	No
2022	Low-High	1.70606E+11	No	No
2022	Low-Low	96522715477	No	No
2023	High-High	3.14812E+11	Yes	Yes
2023	High-Low	1.52655E+11	No	No
2023	Low-High	2.61527E+11	No	No
2023	Low-Low	91990051739	No	No

Table A2. Predicted probabilities of strategy transition per country per year

		Probability				
Country	Year	Next=HH	Next=HL	Next=LH	Next=LL	Current Strategy
France	2010	3.45E-01	1.96E-01	2.41E-01	2.17E-01	LH
France	2011	3.55E-01	1.91E-01	2.40E-01	2.14E-01	LH
France	2012	3.62E-01	1.88E-01	2.39E-01	2.11E-01	LH
France	2013	3.75E-01	1.82E-01	2.37E-01	2.07E-01	LH
France	2014	3.77E-01	1.81E-01	2.36E-01	2.06E-01	LH
France	2015	3.79E-01	1.80E-01	2.36E-01	2.05E-01	LH
France	2016	3.74E-01	1.82E-01	2.37E-01	2.07E-01	LH
France	2017	3.81E-01	1.79E-01	2.36E-01	2.05E-01	LH
France	2018	3.88E-01	1.75E-01	2.35E-01	2.02E-01	LH
France	2019	3.89E-01	1.75E-01	2.34E-01	2.02E-01	LH
France	2020	3.92E-01	1.73E-01	2.34E-01	2.01E-01	LH
France	2021	4.04E-01	1.68E-01	2.32E-01	1.97E-01	LH
France	2022	3.97E-01	1.71E-01	2.33E-01	1.99E-01	LH
Germany	2010	4.45E-01	1.50E-01	2.23E-01	1.82E-01	HH
Germany	2011	4.52E-01	1.47E-01	2.22E-01	1.80E-01	HH
Germany	2012	4.65E-01	1.41E-01	2.19E-01	1.75E-01	HH
Germany	2013	4.97E-01	1.29E-01	2.11E-01	1.64E-01	HH
Germany	2014	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2015	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2016	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2017	5.12E-01	1.23E-01	2.07E-01	1.58E-01	HH
Germany	2018	5.04E-01	1.26E-01	2.09E-01	1.61E-01	HH
Germany	2019	4.93E-01	1.30E-01	2.12E-01	1.65E-01	HH
Germany	2020	4.95E-01	1.29E-01	2.11E-01	1.64E-01	HH
Germany	2021	5.17E-01	1.21E-01	2.06E-01	1.56E-01	HH
Germany	2022	5.35E-01	1.14E-01	2.01E-01	1.50E-01	HH
Italy	2010	3.27E-01	2.06E-01	2.44E-01	2.23E-01	HL
Italy	2011	3.36E-01	2.01E-01	2.43E-01	2.20E-01	HL
Italy	2012	3.45E-01	1.96E-01	2.41E-01	2.17E-01	HL
Italy	2013	3.44E-01	1.97E-01	2.42E-01	2.18E-01	HL
Italy	2014	3.43E-01	1.97E-01	2.42E-01	2.18E-01	HL
Italy	2015	3.38E-01	2.00E-01	2.42E-01	2.20E-01	HL

		Probability				
Country	Year	Next=HH	Next=HL	Next=LH	Next=LL	Current Strategy
Italy	2016	3.35E-01	2.02E-01	2.43E-01	2.21E-01	HL
Italy	2017	3.29E-01	2.05E-01	2.44E-01	2.23E-01	HL
Italy	2018	3.27E-01	2.05E-01	2.44E-01	2.23E-01	LL
Italy	2019	3.39E-01	1.99E-01	2.42E-01	2.19E-01	HL
Italy	2020	3.31E-01	2.04E-01	2.43E-01	2.22E-01	HL
Italy	2021	3.44E-01	1.97E-01	2.42E-01	2.18E-01	HL
Italy	2022	4.09E-01	1.66E-01	2.31E-01	1.95E-01	HL
Netherlands	2010	2.71E-01	2.37E-01	2.49E-01	2.43E-01	LL
Netherlands	2011	2.70E-01	2.37E-01	2.49E-01	2.43E-01	LL
Netherlands	2012	2.69E-01	2.38E-01	2.49E-01	2.43E-01	LL
Netherlands	2013	2.69E-01	2.38E-01	2.49E-01	2.43E-01	LL
Netherlands	2014	2.69E-01	2.38E-01	2.49E-01	2.44E-01	LL
Netherlands	2015	2.69E-01	2.39E-01	2.49E-01	2.44E-01	LL
Netherlands	2016	2.67E-01	2.40E-01	2.49E-01	2.44E-01	LL
Netherlands	2017	2.66E-01	2.40E-01	2.49E-01	2.44E-01	LL
Netherlands	2018	2.68E-01	2.39E-01	2.49E-01	2.44E-01	LL
Netherlands	2019	2.73E-01	2.36E-01	2.49E-01	2.42E-01	LL
Netherlands	2020	2.71E-01	2.37E-01	2.49E-01	2.43E-01	LL
Netherlands	2021	2.73E-01	2.36E-01	2.49E-01	2.42E-01	LL
Netherlands	2022	2.77E-01	2.34E-01	2.49E-01	2.41E-01	LL
Spain	2010	3.23E-01	2.08E-01	2.44E-01	2.25E-01	LL
Spain	2011	3.28E-01	2.05E-01	2.44E-01	2.23E-01	LL
Spain	2012	3.36E-01	2.01E-01	2.43E-01	2.20E-01	LL
Spain	2013	3.34E-01	2.02E-01	2.43E-01	2.21E-01	LL
Spain	2014	3.32E-01	2.03E-01	2.43E-01	2.22E-01	LL
Spain	2015	3.31E-01	2.04E-01	2.43E-01	2.22E-01	LL
Spain	2016	3.24E-01	2.07E-01	2.44E-01	2.25E-01	LL
Spain	2017	3.23E-01	2.08E-01	2.44E-01	2.25E-01	LL
Spain	2018	3.30E-01	2.04E-01	2.43E-01	2.23E-01	HL
Spain	2019	3.29E-01	2.04E-01	2.43E-01	2.23E-01	LL
Spain	2020	3.25E-01	2.07E-01	2.44E-01	2.24E-01	LL
Spain	2021	3.38E-01	2.00E-01	2.42E-01	2.20E-01	LL
Spain	2022	3.86E-01	1.76E-01	2.35E-01	2.03E-01	LL

Table A3. Sensitivity of Key Outcomes to Classification Threshold

Country	Metric	Baseline (τ=50%)	Conservative (τ=40%)	Aggressive (τ=60%)
Germany	HH Frequency (of 14 years)	14	14	14
Germany	Nash Alignment Rate	100%	100%	100%
Germany	Switch Rate	0%	0%	0%
France	HH Frequency	0	0	0
France	Nash Alignment Rate	0%	0%	0%
France	Switch Rate	0%	0%	0%
Italy	HH Frequency	0	12	0
Italy	Nash Alignment Rate	0%	85.7%	0%
Italy	Switch Rate	15.4%	7.7%	15.4%
Netherlands	HH Frequency	0	0	0
Netherlands	Nash Alignment Rate	0%	0%	0%
Netherlands	Switch Rate	0%	7.7%	0%
Spain	HH Frequency	0	1	0
Spain	Nash Alignment Rate	0%	7.1%	0%
Spain	Switch Rate	7.7%	15.4%	7.7%
All countries	HH share (% of all country-years)	20.0%	38.6%	20.0%
All countries	Avg. Nash Alignment	20.0%	38.6%	20.0%
All countries	Avg. Switch Rate	6.2%	6.2%	6.2%

References

Awerkin, A., & Vargiolu, T. (2021). Optimal installation of renewable electricity sources: The case of Italy. *Decisions in Economics and Finance, 44*(2), 1179–1209. https://doi.org/10.1007/s10203-021-00365-4

Backe, S., Kara, G., & Tomasgard, A. (2020). Comparing individual and coordinated demand response with dynamic and static power grid tariffs. *Energy, 201*, 117619. https://doi.org/10.1016/j.energy.2020.117619

Bastianon, E. (n.d.). Optimizations according Nash and Pareto for the equilibria in ECB's monetary policy assessment of model. https://www.academia.edu/24977848/

Cadre, H. L. (2019). On the efficiency of local electricity markets under decentralized and centralized designs: A multi-leader Stackelberg game analysis. *Central European Journal of Operations Research, 27*(4), 953–984. https://doi.org/10.1007/s10100-018-0521-3

Cheng, L., Huang, P., Zhang, M., Ru, Y., & Wang, Y. (2025). Optimizing electricity markets through game-theoretical methods: Strategic and policy implications for power purchasing and generation enterprises. *Mathematics, 13*(3), 373. https://doi.org/10.3390/math13030373

Dimitriadis, C. N., Tsimopoulos, E. G., & Georgiadis, M. C. (2021). A review on the complementarity modelling in competitive electricity markets. *Energies, 14*(21), 7133. https://doi.org/10.3390/en14217133

Dotoli, M., Epicoco, N., Falagario, M., Sciancalepore, F., & Costantino, N. (2014). A Nash equilibrium simulation model for the competitiveness evaluation of the auction-based day-ahead electricity market. *Computers in Industry, 65*(4), 774–785. https://doi.org/10.1016/j.compind.2014.02.014

Egerer, J., Weibezahn, J., & Hermann, H. (2016). Two price zones for the German electricity market – Market implications and distributional effects. *Energy Economics, 59*, 365–381. https://doi.org/10.1016/j.eneco.2016.08.002

Eurostat. (2023). Electricity market indicators. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_market_indicators

Grimm, V., Martin, A., Schmidt, M., Weibelzahl, M., & Zöttl, G. (2016). Transmission and generation investment in electricity markets: The effects of market splitting and network fee regimes. *European Journal of Operational Research, 254*(2), 493–509. https://doi.org/10.1016/j.ejor.2016.03.044

Gugler, K., Liebensteiner, M., & Schmitt, S. (2017). Vertical disintegration in the European electricity sector: Empirical evidence on lost synergies. *International Journal of Industrial Organization, 52*, 450–478. https://doi.org/10.1016/j.ijindorg.2017.04.002

Hu, Z., Zhu, Z., Wei, X., Chan, K. W., & Bu, S. (2025). Mixed strategy Nash equilibrium analysis in real-time pricing and demand response for future smart retail market. *Applied Energy, 391*, 125815. https://doi.org/10.1016/j.apenergy.2025.125815

Huppmann, D., & Egerer, J. (2015). National-strategic investment in European power transmission capacity. *European Journal of Operational Research, 247*(1), 191–203. https://doi.org/10.1016/j.ejor.2015.05.056

Kang, K., Su, Y., Yang, P., Wang, Z., Zhang, Y., Qi, N., & Liu, F. (2025). Understanding cross-market strategic behaviors of prosumers: An equilibrium-driven evolutionary game approach. *Journal of Cleaner Production, 513*, 145345. https://doi.org/10.1016/j.jclepro.2025.145345

Kim, H. J., Chung, Y. S., Kim, S. J., Kim, H. T., Jin, Y. G., & Yoon, Y. T. (2023). Pricing mechanisms for peer-to-peer energy trading: Towards an integrated understanding of energy and network service pricing mechanisms. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2023.113435

Kunz, F., & Zerrahn, A. (2016). Coordinating cross-country congestion management: Evidence from Central Europe. *The Energy Journal, 37*, 81–100. https://doi.org/10.5547/01956574.37.SI3.fkun

Mezghani, I., Papavasiliou, A., & Le Cadre, H. (2018). A generalized Nash equilibrium analysis of electric power transmission-distribution coordination. In *E-Energy 2018 Proceedings of the 9th ACM International Conference on Future Energy Systems* (pp. 526–531). https://doi.org/10.1145/3208903.3214346

Navon, A., Ben Yosef, G., Machlev, R., Shapira, S., Chowdhury, N. R., Belikov, J., Orda, A., & Levron, Y. (2020). Applications of game theory to design and operation of modern power systems: A comprehensive review. *Energies, 13*(15), 3982. https://doi.org/10.3390/en13153982

Oggioni, G., & Smeers, Y. (2012). Degrees of coordination in market coupling and counter-trading. *The Energy Journal, 33*(3), 39–90. https://doi.org/10.5547/01956574.33.3.3

Oggioni, G., Allevi, E., & Schaible, S. (2012). A generalized Nash equilibrium model of market coupling in the European power system. *Networks and Spatial Economics, 12*(4), 503–560. https://doi.org/10.1007/s11067-011-9166-7

Oggioni, G., Murphy, F. H., & Smeers, Y. (2014). Evaluating the impacts of priority dispatch in the European electricity market. *Energy Economics, 42*, 183–200. https://doi.org/10.1016/j.eneco.2013.12.009

Oggioni, G., & Smeers, Y. (2013). Market failures of market coupling and counter-trading in Europe: An illustrative model-based discussion. *Energy Economics, 35*, 74–87. https://doi.org/10.1016/j.eneco.2011.11.018

Paola, A. D., Angeli, D., & Strbac, G. (2018). On distributed scheduling of flexible demand and Nash equilibria in the electricity market. *Dynamic Games and Applications, 8*(4), 761–798. https://doi.org/10.1007/s13235-017-0237-3

Pfeifer, A., Feijoo, F., & Duić, N. (2023). Fast energy transition as a best strategy for all? The Nash equilibrium of long-term energy planning strategies in coupled power markets. *Energy, 284*, 129109. https://doi.org/10.1016/j.energy.2023.129109

Soriano, L. A., Avila, M., Ponce, P., Rubio, J. d. J., & Molina, A. (2021). Peer-to-peer energy trades based on multi-objective optimization. *International Journal of Electrical Power & Energy Systems, 131*, 107017. https://doi.org/10.1016/j.ijepes.2021.107017

Tang, J., Qian, B., Luo, Y., Lin, X., Zhou, M., Zhang, F., & Wang, H. (2025). Evolutionary game theory-based analysis of power producers' carbon emission reduction strategies and multi-group bidding dynamics in the low-carbon electricity market. *Processes, 13*(4), 952. https://doi.org/10.3390/pr13040952

Tutz, G., Pößnecker, W., & Uhlmann, L. (2015). Variable selection in general multinomial logit models. *Computational Statistics & Data Analysis, 82*, 207–222. https://doi.org/10.1016/j.csda.2014.09.009

Wang, H., Xie, Z., Pu, L., Ren, Z., Zhang, Y., & Tan, Z. (2022). Energy management strategy of hybrid energy storage based on Pareto optimality. *Applied Energy, 327*, 120095. https://doi.org/10.1016/j.apenergy.2022.120095

Yarar, N., Yoldas, Y., Bahceci, S., Onen, A., & Jung, J. (2024). A comprehensive review based on the game theory with energy management and trading. *Energies, 17*(15), 3749. https://doi.org/10.3390/en17153749

Zahid, F. M., & Tutz, G. (2013). Multinomial logit models with implicit variable selection. *Advances in Data Analysis and Classification, 7*, 393–416. https://doi.org/10.1007/s11634-013-0136-4