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EU ETS Price Signals in the Power Sector: Evidence on Decarbonisation and Policy Overlap

Giacomo Di Foggia *, **Massimo Beccarello and Bakary Jammeh**

Department of Business and Law, University of Milano-Bicocca, Via Bicocca degli Arcimboldi 1, 20126 Milan, Italy
* Correspondence: giacomo.difoggia@unimib.it

Abstract

Understanding the role of carbon pricing and complementary support schemes in renewable energy deployment is increasingly important for the decarbonisation of power markets. The analysis employs a mixed-methods approach: a panel econometric analysis of installed renewable capacity across European countries from 2013 to 2024, a cross-country survey involving 127 firms, and an hourly market-based estimation of inframarginal rents. Econometric evidence indicates that energy and fuel subsidies consistently drive the expansion of renewable energy capacity. The survey results corroborate that investors prioritise subsidies, regulatory stability, and long-term revenue certainty over the price of EU allowances in renewable energy investment decisions. The market-based analysis demonstrates that the system primarily influences the power sector through wholesale electricity price formation and carbon cost pass-through, thereby generating persistent inframarginal revenues for low-carbon technologies. A comparison between the regulatory carbon factors used for indirect cost compensation and the observed market-based pass-through indicators reveals substantial cross-country differences. The evidence suggests that the system currently functions more as a mechanism for wholesale price transmission and revenue redistribution than as an independent driver of renewable energy investment, underscoring the importance of complementary support policies and electricity market design.

Keywords: EU ETS; carbon price; renewable energy; inframarginal rents; emission trading; electricity market; SDG 7; subsidies; EU

1. Introduction

In the current economic landscape, carbon pricing schemes must achieve two goals: reduce emissions and safeguard the competitiveness of economic systems [1]. Reaching Sustainable Development Goal 7 (SDG 7) requires a holistic approach that combines environmental policies with market-based instruments. Since its introduction, the EU Emissions Trading System (EU ETS) has represented one of the most advanced applications of a market-based environmental policy instrument within a large, integrated economic area [2,3]. Unfolding its role in the decarbonisation of the power sector is important because electricity generation is fully exposed to the carbon price and therefore offers the most direct setting for verifying whether the EU ETS has effectively generated observable adjustment dynamics. Without moving toward a more sustainable energy mix by increasing the installed renewable energy capacity, economic growth and energy intensity can worsen environmental quality, and environmental taxes can play a significant role in shaping policy. In fact, the decoupling of growth from environmental impacts is more effective in countries with greater ecological capacity [4]. Unsurprisingly, decarbonisation policies

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increasingly rely on a combination of carbon pricing, regulatory intervention, industrial policy, infrastructure deployment, and public support mechanisms intended to accelerate technological transformation and guide long-term investments.

In the power sector, the carbon price directly affects the marginal cost of fossil-based generation, alters the relative competitiveness of generation technologies, and may therefore influence both short-term dispatch decisions and medium-term investment choices [5,6]. Therefore, the power sector serves as a benchmark for assessing whether the EU ETS has effectively contributed to the decarbonisation of the energy mix [7,8]. The recent literature suggests that both carbon pricing and subsidies matter; nevertheless, they operate through different channels: targeted subsidies directly support renewable energy investment, whereas carbon pricing provides a market-based price signal that improves the relative competitiveness of low-carbon technologies [9–11]. A mixed-method triangulation approach combines evidence on renewable deployment, market participants' perceptions of investment drivers, and electricity price formation, including carbon-related inframarginal rents (IMRs), through which the carbon price signal can affect renewable investment incentives. The empirical strategy is based on the following research questions (RQs): RQ1. What are the factors associated with renewable-capacity deployment in the EU power sector, and what is the role of the overlap between the EUA price signal and subsidies? RQ2. How do renewable investors rank the relative importance of carbon pricing, subsidies, long-term support schemes, and regulatory stability when making investment decisions in renewable generation and storage? RQ3. To what extent do the estimated market-based indicators suggest that costs are passed through to wholesale electricity prices, and what is the magnitude of the associated IMRs accruing to clean generation? To answer these questions, we combine three complementary empirical approaches: panel econometric analysis, an international survey of market participants, and an hourly market-based analysis of electricity price formation and carbon price pass-through (CPT). Evidence confirms that subsidies are associated with renewable capacity expansion while underscoring the central role of long-term contractual arrangements and revenue-stabilisation mechanisms in supporting investment decisions and project bankability [11,12]. Simultaneously, the EU ETS operates alongside renewable energy development. The most economically significant effect of the EU ETS in power markets is the generation of persistent inframarginal revenues for low-carbon technologies through marginal price formation. Moreover, comparisons between REF used to compensate for indirect EU ETS costs and observed market-based CPT indicators reveal significant divergences across countries.

Within European electricity markets, carbon price signals operate more directly as wholesale electricity price transmission and revenue redistribution mechanisms. Future reform discussions increasingly require a more explicit assessment of the interactions among carbon pricing, electricity market design, renewable support schemes, and long-term investment-favourable conditions.

Despite the literature on the EU ETS and renewable energy policies, three knowledge gaps persist. First, while numerous studies have examined the relationship between carbon pricing and the uptake of renewable energy sources, less attention has been given to whether carbon pricing has an independent effect on the expansion of renewable capacity once subsidies are considered. Second, empirical evidence on how market participants assess the relative importance of carbon pricing, subsidies, regulatory stability, and long-term revenue certainty is limited. Third, the literature has analysed EPT, but less attention has been given to how the price signal is transmitted through wholesale electricity markets via marginal price formation and resulting IMRs.

We fill this gap by combining these three complementary perspectives within a single analytical framework to provide a more comprehensive assessment of the channels

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through which carbon prices influence the deployment of renewable energy sources and the outcomes of electricity markets.

The remainder of this paper is organised as follows. Section 2 reviews the three strands of literature relevant to the analysis, that is, the policy-mix debate, investor decision-making and bankability, and CPT with IMRs, and derives the three working hypotheses from each strand, together with the conceptual background of the mixed-methods approach. Section 3 presents the research design, analytical framework, survey methodology, and inframarginal rent identification strategy. Section 4 reports the econometric results, survey evidence, and empirical estimates of EU ETS-related rents (EIR) and indirect compensation factors. Section 5 discusses the findings in light of the literature and highlights policy implications. Finally, Section 6 concludes the study.

2. Literature Review

In the canonical economic–environmental framework, a credible carbon price internalises the externality and improves the relative competitiveness of low-carbon technologies through its impact on wholesale electricity prices; thus, the EU ETS should incentivise the reallocation of capital to clean technologies [7]. Based on this approach, the conditions under which a cap-and-trade system can coexist effectively with other climate policy instruments, such as environmental taxes and direct subsidies, are analysed, highlighting policy overlap and interaction, a central aspect of this analysis [5]. Another study provides a systematic review of the interaction between emissions trading schemes and renewable energy subsidies, showing how the two instruments can operate in a complementary or substitutive manner, depending on the configuration of the incentive regime and the stringency of the emissions cap [13]. Two distinct positions have emerged in the literature on this topic. On the one hand, several contributions have argued that, with appropriate design improvements, the EUA price signal can be made strong enough to act as a primary investment driver. Flachsland et al. revisited the case for an EU EUA price floor and argued that, despite the recent reform and the Market Stability Reserve, design flaws related to credibility, myopia, and waterbed effects persist and that a price floor would enhance the predictability of the EUA price and, therefore, its role as an investment signal [14]. Pahle et al. [15] developed a complementary argument from the perspective of policy sequencing: barriers to climate policy stringency can be overcome over time through the deliberate sequencing of instruments, with carbon pricing progressively increasing as political and economic constraints are relaxed [15]. In this view, the EUA price has the potential to become a sufficient driver of renewable investment once policy credibility issues are addressed. Empirical support for this position is provided by another study that uses a synthetic-control approach on sectoral emissions data and estimates that the EU ETS saved more than one billion tonnes of CO_2 between 2008 and 2016, equivalent to a 3.8% reduction relative to a counterfactual without the ETS, even during the period of historically low allowance prices, providing direct evidence that the system can deliver measurable abatement before reform [16].

However, an increasing body of literature suggests that, in practice, direct support instruments dominate the EUA price as drivers of renewable deployment. Lecuyer and Quirion [17] show, in a model with uncertainty over electricity demand, renewable costs, and gas prices, that feed-in tariffs are welfare-improving as a safety net against EU ETS overallocation. For example, it is argued that subsidy-type renewable instruments outperform renewable portfolio standards in terms of emission reduction once carbon pricing is in place [18]. At the same time, a similar article examining the case for supporting renewable electricity develops a learning-by-doing argument that justifies initial subsidies in their own right, independent of any carbon-price effect [6].

Recent reviews of policy mixes for energy transition have highlighted a broadly consistent conclusion. In a systematic literature review on environmental policies and renewable energy innovation, Rastegar et al. document that targeted subsidies and feed-in instruments are repeatedly identified as the most effective tools for the early deployment of renewable energy. Moreover, carbon pricing tends to play a complementary role [9,19]. In their empirical analysis of the G7 countries, Liu et al. reported that environmental regulation and financial development jointly drive the renewable transition, with direct support instruments being persistently dominant [11]. Lin and Jia reported that an EU ETS without revenue recycling into renewables may reduce renewable generation [10]. Another study provides evidence that higher permit volumes (looser caps) are associated with a lower share of renewable energy [20]. Moreover, a previous analysis revealed that overlapping policies and recession effects drove the post-2008 collapse of the EUA price, reminding us that the EUA price signal is endogenous to the broader policy mix [21]. The question our study addresses is whether the EUA price has been a direct driver of renewable-capacity deployment or whether subsidies have absorbed the bulk of the explanatory power. This leads to the following pair of hypotheses: H1.0. The EUA price signal alone has a statistically significant positive effect on installed renewable capacity once macroeconomic conditions are controlled for; that is, the EUA price operates as a direct driver of renewable deployment in the EU power sector. H1.1. Subsidies are the dominant driver of installed renewable capacity, while the EUA price has no independent effect once direct support is controlled for; the two instruments may also interact (overlap effects).

Within a framework of internalised externalities, the carbon price should be the dominant marginal signal for investment in low-carbon technologies [7]. If this view holds at the level of investment decisions, then the price of EUAs should be perceived by investors as the most important driver of investment. However, a growing body of the empirical literature points in a different direction, highlighting that direct support, regulatory predictability, and revenue-stabilisation instruments outweigh carbon-pricing instruments in shaping investor behaviour [12]. It has also been reported that investment in renewable energy and clean technology is driven primarily by long-term financial structures and revenue-stabilisation mechanisms, with carbon-pricing instruments playing a secondary role in actual capital allocation [22]. To the same extent, financial development and environmental regulation jointly support the renewable transition, with revenue-stabilisation instruments being decisive in project financing [11]. Theoretical and modelling contributions reinforce this picture. Bublitz et al. review electricity market design and report that, under capacity remuneration mechanisms and the presence of long-term contracts, the marginal value of the carbon price for investment decisions is partially offset by other revenue streams [23]. Aflaki and Netessine report that, under market and intermittency conditions typical of European electricity systems, carbon taxes alone can even reduce incentives to invest in intermittent renewables because of the interaction between risk and supply variability and revenue formation [24]. We test whether investors and energy utilities perceive the EUA price as the most important driver of investment in renewable generation and storage projects or whether they consider subsidies above the EUA price as the primary driver of investment decisions. H2.0. Investors perceive the EUA price as the primary driver of investment decisions in renewable generation and energy storage projects. H2.1. Investors perceive direct public support, regulatory stability, and long-term revenue certainty as more important drivers of investment decisions than the EUA price.

The mechanism by which the EU ETS shapes wholesale electricity prices and the resulting distribution of rents across generation technologies is significant. In their analysis of free-allocation effects in the power sector, Sijm et al. document that European power companies pass on the cost of the EU ETS through electricity prices, with empirical and model-based CPT rates ranging from 60% to 100% of CO_2 costs in Germany and the Netherlands [25]. They show that CPT depends on the carbon intensity of the marginal production unit and market- and technology-specific factors. The structural consequence of this EPT under marginal pricing is the generation of IMRs for low-carbon technologies that do not bear equivalent carbon costs but receive the market price set by fossil units. Keppler and Cruciani [26] provide the first quantitative assessment of these rents for the European power sector during the early phases of the system, establishing an analytical framework that the present study extends to a more recent period and a broader country panel. Fabra and Reguant [27] deepen the theoretical and empirical analysis of CPT in the Spanish wholesale electricity market and confirm that, under marginal pricing, carbon costs are substantially passed through, with the magnitude depending on the market structure and technology setting the marginal price. The aforementioned studies converge on the finding that EPT and IMRs are properties of marginal-pricing electricity markets in which fossil technologies set the price. Recent contributions show that the identity of price-setting technology is heterogeneous across countries and over time, with direct implications for the CPT. For example, fossil-fuel-based plants set electricity prices in Europe approximately 58% of the time, with natural gas alone setting prices 39% of the time, while generating only approximately 34% of electricity [28]. This mismatch between the share of generation and the share of price setting produces IMRs. Increasing wind and photovoltaic generation lowers spot prices through the merit-order effect; this result mirrors the inframarginal-rent mechanism and confirms that wholesale prices in European markets are sensitive to which technology sets the margin [29]. Blume-Werry et al. provide a comparative analysis of price-setting technologies across European electricity markets, confirming substantial cross-country heterogeneity [30]. Duttilo and Lisi [31] estimate the EPT rate in the power system and confirm that its magnitude is materially influenced by the frequency of fossil price setting and the carbon intensity of the marginal unit. This body of evidence has direct implications for the state aid framework for indirect EU ETS cost compensation. The framework relies on the REF, derived from structural averages of fossil generation across predefined regional areas. If the actual CPT varies materially with the frequency of fossil price setting, structural averages may diverge from observed market-based factors [28]. Thus, the extent of this divergence has received limited systematic attention in the literature, and this study makes an empirical contribution in this area. Our hypothesis on price formation and CPT is as follows: H3.0. The observed market-based CPT, estimated from the hourly identification of the price-setting technology, is broadly aligned with the REF used in the state aid framework for indirect EU ETS cost compensation. H3.1. Observed market-based CPT factors diverge materially from regulatory CO_2 factors, particularly in MS, where the marginal price is set by fossil generation only in a minority of hours; EIRs accruing to clean generation are accordingly substantial and persistent. Each of the three hypotheses derived above is best tested through a distinct empirical lens: panel econometrics for H1, an investor survey for H2, and hourly market-based estimation for H3. To address the complexity of decarbonisation, we adopted a triangulation approach that combined multiple methods, datasets, and analytical perspectives to provide a more robust and comprehensive interpretation of the empirical evidence. Triangulation involves using multiple methods and data sources to study the same phenomenon. Reading the three lenses together, as triangulation prescribes, provides us with the insight to test the same overarching question under three different conceptual backgrounds; their convergence strengthens the credibility of our inferences.

3. Materials and Methods

First, the analytical framework used to assess the drivers of renewable capacity development, including the econometric specification of the panel model, dependent and explanatory variables, geographical and temporal coverage, and identification strategy, is presented. An international survey on the drivers of investment in renewable energy and storage systems is then described. The identification strategy for pricing technologies and the estimation of the transfer of carbon costs to wholesale electricity prices were then analysed. Finally, the methodological scope and limitations are discussed. The empirical strategy is illustrated in Figure 1.

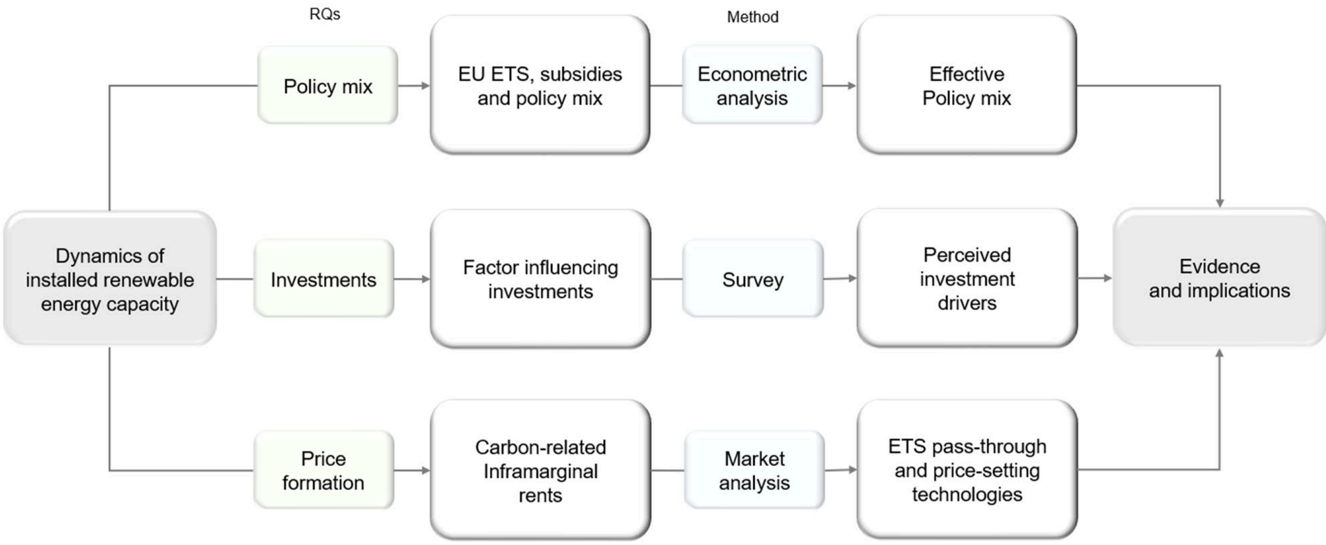

Figure 1. Research framework. Source: the authors. The first path investigates the interaction between support schemes, EUA price signals, and policy overlap through panel econometric analysis. The second examines the role of investment conditions and perceived investment drivers through an international survey of firms and their investors. The third analyses EIR and electricity price formation by identifying price-setting technologies and estimating market-based CPTs. The solid boxes denote conceptual constructs and outputs, and the dashed boxes denote hypotheses (H1–H3) and methods.

The dependent variable is the installed renewable capacity in megawatts (MW) (source: EMBER). The key explanatory variables are energy and fuel subsidies (source: EUROSTAT, General government expenditure by function. Sector: General government. COFOG99: Fuel and Energy. ESA 2010: Subsidies. Online data code: gov_10a_exp); therefore, the variable should be interpreted as a proxy for subsidies for the energy transition rather than a pure measure of renewable energy subsidies. It was selected because it is the only harmonised dataset with broad country coverage and a consistent annual time series. The EUA is the allowance price in Europe (source: EEX). The control variables include verified power sector emissions, which serve as a proxy for decarbonisation pressure (source: Emission Trading System Union Registry, Verified emissions 2024), and gross domestic product (GDP) to control for the economic cycle (source: EUROSTAT). Table 1 describes the variables used in the analysis of the drivers of renewable capacity development. The relative EUA price was obtained by interacting the carbon price with the fossil share of the energy mix across countries.

Table 1. Descriptive statistics.

Variable	Description	Obs	Mean	Std. Dev.	Min	Max
cap	Capacity (MW)	359	10,882.44	22,222.85	0	165,564
esub	Support schemes	341	2425.46	5930.94	0	50,744
eua	EUA (€/t)	360	31.64	29.66	4.33	83.66
eve	Verified emissions (power sector)	360	27,000	54,600	0	352,000
gdp	GDP per capita	359	38,145	30,733.24	5870.00	185,840
eua_fsh	EUA × fossil share	348	2246.21	2191.22	117.88	7168.66
ccapex	Capital expenditure	249	4.056	0.887	1	5
eua	EUA price	248	3.931	0.895	1	5
gasp	Natural gas price	253	4.111	0.866	1	5
proc	Procurement (e.g)	253	4.028	0.852	1	5
esub	Subsidies	252	4.099	0.843	2	5
reg	Regulatory stability	251	4.139	0.805	2	5

Source: the authors. The support scheme variable esub does not exclusively capture renewable energy support. However, comparisons with more detailed national data available for selected Member States indicate that renewable energy support represents a substantial component of the broader COFOG99 subsidy measure.

The survey used only a subset of questions directly relevant to the research objectives. The respondents were selected through purposive sampling and comprised professionals directly involved in renewable energy investment decisions, such as energy utilities, renewable project developers, and specialised financial investors. The six countries were selected to represent the principal EU ETS markets while ensuring geographical diversity of the sample. As the respondents evaluated both renewable generation and energy storage projects, the unit of analysis was the project rather than the individual respondent. Accordingly, the number of observations reported in the descriptive statistics exceeded the number of participants in the survey. The survey sample (127 respondents) was distributed across six countries, with larger subsamples in Italy, France, Spain, and Germany. Italy accounted for 25.1% of the responses, followed by France (20.5%), Spain (19.9%), Germany (20.3%), Poland (7.1%), and Sweden (7.1%). Medium-sized and large firms dominated the sample, and 37.8% of the respondents were C-level executives in the sample. The hourly panel covers eight EU MS—Belgium, France, Germany, Italy, the Netherlands, Poland, Spain, and Sweden—and is assembled from the ENTSO-E Transparency Platform. Four ENTSO-E datasets were used: day-ahead prices (12.1. D), aggregated generation per type (16.1. B/C), actual total load (6.1. A) and physical flows/scheduled commercial exchanges (12.1.F/G). The dataset codes refer to the corresponding articles of Commission Regulation (EU) No. 543/2013. The technical parameters are listed in Table 2.

Table 2. Technical parameters.

Parameter	Value	Notes
Gas efficiency	0.55	Average CCGT conversion efficiency
Coal efficiency	0.38	Average coal plant conversion efficiency
Gas emission factor	0.37 tCO_2/MWh	CO_2 intensity per MWh of electricity generated
Coal emission factor	0.90 tCO_2/MWh	CO_2 intensity per MWh of electricity generated
Residual threshold	0.20	Residual load/total load threshold

Regarding the residual threshold, the residual-load threshold is introduced as a prudential operational assumption to exclude hours characterised by very low residual demand, where standard merit-order dynamics may be less representative of actual price-formation mechanisms.

Each record was assigned to one of the eight target countries by matching the ENTSO-E map code, area code, and area display name. Table 3 shows the descriptive statistics.

The aggregation rule prefers the exact country row whenever available; otherwise, the country value is obtained by summing subzone values for load, generation, and cross-border flows, applied in particular to Italy (seven bidding zones) and Sweden (SE1–SE4), with the German–Luxembourg DE-LU price area treated as a single national observation.

Table 3. Descriptive statistics of marginal price.

Variable	Obs	Mean	Std. Dev.	Min	Max
Gas share	32	0.449	0.234	0.001	0.875
Coal share	32	0.060	0.088	0.000	0.293
Other share	32	0.491	0.252	0.041	0.999
Gas Hours	32	3937.750	2049.529	12.000	7689
Coal Hours	32	526.406	768.819	0.000	2566
Other Hours	32	4301.844	2212.024	363.000	8748
Observed Factor	32	0.220	0.119	0.001	0.437

Source: the authors.

For multizone countries, the national price was computed as the load-weighted average of zonal prices. Generation by technology was reduced to six standardised categories—gas, coal, nuclear, wind, solar, and hydro—by string matching the ENTSO-E production-type field. Cross-border physical flows were processed in directional pairs; same-country zone-to-zone flows were excluded to avoid double-counting. Fuel price series (TTF gas and international coal benchmarks) were retrieved from FactSet, and EUA market prices were retrieved from EEX.

3.1. Empirical Analysis

A mixed-methods approach was adopted to provide a comprehensive interpretation of the empirical evidence via triangulation of the methods and data sources. In economics, it often involves combining quantitative statistical analysis with qualitative evidence to better reflect reality and enable the integration of different insights [32]. Triangulation supports empirically based hypothesis construction and theory modification [33], method innovation [34], and rebalancing fields dominated by a single paradigm by institutionalising multiple methods to avoid systematic bias [32,35]. Although divergent results are common, we agree that they can yield a more insightful understanding and new concepts than a single approach [36].

Renewable development

From a theoretical perspective, the carbon price is expected to indirectly influence renewable energy investments by enhancing the competitiveness of low-carbon technologies; consequently, the log of installed renewable capacity (MW) is the dependent variable. However, this transmission may be partial or uncertain because of electricity market design, regulatory interventions, and carbon price volatility [21,23]. In contrast, subsidies act more directly on investment decisions by increasing expected returns and reducing financing constraints [37]. The empirical framework allows the testing of three key hypotheses: whether subsidies are a significant and robust driver of installed renewable capacity; whether the EUA price exerts an independent effect on renewable investment; and whether the interaction between the two policy instruments indicates complementarity or substitution. The analysis is based on an annual panel of 31 European countries participating in the EU ETS from 2013 to 2024. The balanced dataset contains 402 country-year observations, while the effective estimation sample ranges from 295 to 306 observations depending on the model specification due to the one-period lag applied to the key explanatory variables, the exclusion of Norway in selected specifications, and the presence of missing values for some of the explanatory variables. The empirical model is formulated in Equation (1).

$$\begin{aligned} ln(cap_{it}) = \; & \beta_1 ln(esub_{i,t-1}) + \beta_2 ln(eua_{i,t-1}) \\ & + \beta_3[\ln(esub_{i,t-1}) \times \ln(eua_{i,t-1})] \\ & + \beta_4 ln(eve_{it}) + \beta_5 ln(gdp_{it}) + \alpha_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{1}$$

The key explanatory variables include public support for renewable energy, proxied by the logarithm of general government expenditure on energy and fuel subsidies (Eurostat, COFOG99), the EUA price, and their interaction term. In the baseline specification, the EUA price is constructed at the country level using granular primary-auction data from the European Energy Exchange (EEX). Primary-auction observations were aggregated to obtain annual average EUA prices for each country, aiming to present the country-specific even small variation observed in the auction data. Accordingly, the EUA coefficient is identified from within-country variation over time, together with the remaining cross-country heterogeneity in the country-specific EUA series that is not absorbed by the fixed effects. As an alternative specification, the EUA price is normalised by the country-specific industrial natural gas price, generating a relative carbon price indicator that captures differences in national energy market conditions. The control variables include the logarithm of verified emissions from the power sector, which captures structural decarbonisation pressure, and the logarithm of GDP per capita, which controls for differences in economic development and business-cycle conditions. Since utility-scale renewable investments require planning, permitting, financing, construction, and grid connection, the main explanatory variables enter the model with a one-year lag. This specification reflects the expected delay between policy incentives and realised investment decisions while also reducing concerns about contemporaneous reverse causality. As an additional robustness exercise, models with two-year lags are estimated and reported in the Appendix A. Several countries reported zero expenditures on subsidies in specific years. Because the logarithmic transformation is undefined at zero, these observations were excluded from the baseline estimation sample. As a robustness check, the analysis was replicated using the log(1 + x) transformation, which retains zero observations and yields qualitatively unchanged results. The model was estimated as a two-way fixed-effects panel model with country and year fixed effects, with standard errors clustered at the country level to account for heteroscedasticity and serial correlation [38]. By exploiting both within-country variation over time and cross-country differences in policy design, the model investigates the determinants of renewable-capacity development, paying particular attention to the role of carbon pricing and subsidies and whether these instruments operate as complements or substitutes in supporting the energy transition.

Survey on renewable energy investment drivers

An international survey was commissioned across six countries (Italy, France, Spain, Germany, Poland, and Sweden), focusing on the main EU economies participating in the ETS. The respondents were selected from energy utilities and project developers active in renewable energy generation and storage, as well as from financial intermediaries and investors specialising in green and low-carbon technologies. The questionnaire was divided into an introductory section on demographic and professional characteristics, a section on route-to-market strategies and revenue structures, a central section on factors boosting investment in renewable energy and storage, and a section on market, regulatory, and financial constraints. Most questions used five-point Likert scales, allowing for a comparable measurement of the degree of importance respondents attributed to the various factors considered. The survey is part of a broader research project on renewable-energy investment drivers in Europe. A total of 127 respondents participated in the survey. Because respondents could evaluate more than one project category (e.g., renewable generation and energy storage), the analytical dataset contained more project-level observations than individual respondents. Accordingly, the descriptions refer to project-level observations rather than unique respondents. The survey is intended to provide descriptive and exploratory evidence that complements the econometric analysis. The survey was commissioned to TOLUNA SA and countries were purposively selected to represent different economic and energy-system characteristics.

Price-setting technologies

The estimation of IMRs is grounded in a set of simplifying but economically consistent assumptions regarding the functioning of wholesale electricity markets. The analysis builds on the marginal pricing framework, according to which electricity prices are determined hourly by the marginal unit, defined as the last generation technology dispatched to meet demand [28,30]. Under this assumption, the observed day-ahead market price is interpreted as a proxy for the marginal cost of price-setting technology.

The empirical implementation combines hourly electricity market data with daily fuel price series and EUAs. Day-ahead electricity prices and hourly generation by technology are matched with daily observations of fuel prices (TTF for gas and international coal benchmarks). Within this framework, the marginal cost of fossil technologies is constructed by explicitly accounting for plant efficiency and emission intensity. Fuel prices were converted into electricity-equivalent marginal costs by dividing them by the assumed conversion efficiency of the relevant technology. In contrast, the carbon cost component is calculated by multiplying the EUA price by the corresponding emission factor per unit of electricity produced, as formalised in Equations (2) and (3).

$$MC_{gas} = \frac{Gas}{\eta_{gas}} + EUA \times EF_{gas} \tag{2}$$

and

$$MC_{coal} = \frac{Coal}{\eta_{coal}} + EUA \times EF_{coal} \tag{3}$$

The baseline assumptions are η_gas = 0.55 for combined-cycle gas turbines, η_coal = 0.38 for coal-fired generation, EF_gas = 0.37 tCO_2/MWh, and EF_coal = 0.90 tCO_2/MWh, which are consistent with the standard engineering values reported by the International Energy Agency [39], the Intergovernmental Panel on Climate Change [40], and the European Commission Joint Research Centre [41]. A prudential residual-load threshold of 0.20 (residual load over total load) is introduced to exclude hours characterised by very low residual demand conditions, where standard merit-order dynamics may be less representative of actual price formation.

The identification of marginal technology follows a rule-based classification operationalising merit-order logic. For each hour, the observed electricity prices are compared with the estimated marginal costs of gas and coal. When the observed price is compatible with the estimated marginal cost of gas and gas-fired generation, the hour is classified as gas; when the observed price is compatible with the estimated marginal cost of coal and coal generation, the hour is classified as coal; and the remaining observations are assigned to a residual category. Operationally, compatible was defined as a nearest-marginal-cost rule with a joint generation condition: for each hour h, the observed day-ahead price P_h is compared with the estimated marginal costs $MC_{gas,h}$ and $MC_{coal,h}$, and h was assigned to the fossil fuel either gas or coal, that minimises $\left[P_h - MC_{f,h}\right]$, conditional on fossil technology generating a positive quantity during the hour; hours in which neither gas nor coal is generating, or in which the residual-load fraction falls below the 0.20 threshold, are assigned to the residual category. Consistent with the comparative, order-of-magnitude interpretation adopted throughout, this rule is not intended to reconstruct the hour-by-hour price setter but to preserve the relative shares of gas and coal set hours for subsequent aggregation.

Based on this, an effective EU ETS transmission factor is constructed by assigning the emission factor of the identified marginal technology to each hour and aggregating it over time. IMRs are then estimated by isolating the EU ETS-related component of electricity prices and attributing it to inframarginal generation (wind, solar, and hydro), which does not bear equivalent carbon costs but receives the market price set by fossil units.

3.2. Methodological Limitations

The triangulation approach adopted in this study enhances the robustness of the findings by combining econometric evidence, survey results, and market-data analyses. However, this research is not without its limitations. Econometric analysis is constrained by data availability and the relatively limited time period considered, which encompasses a succession of exceptional events, including the COVID-19 pandemic, the subsequent energy crisis, and geopolitical tensions. This makes it difficult to identify the specific effect of the ETS's price signal. Furthermore, the survey covered six MSs and a relatively small number of respondents. Although the sample included decision makers directly involved in investment processes, it cannot be considered statistically representative of the entire population of market operators. Moreover, the survey focused primarily on energy utilities, project developers, and financial investors without systematically including other relevant stakeholders. The inframarginal rent estimation approach should be interpreted as a stylised representation of market dynamics. Cross-border physical flows are used only to aggregate national load and generation across multizone countries correctly and to avoid double-counting subzone contributions; they are not modelled as a channel that affects the identification of the price-setting technology, so network constraints and congestion effects are not captured. Strategic bidding behaviour and other market imperfections are not modelled. As a result, the estimated marginal technologies and associated EPTs should be regarded as representative indicators of underlying market conditions rather than exact hour-by-hour reconstructions. The analysis relies on publicly accessible market and generation data; National Regulatory Authorities and ACER could develop more granular assessments within the broader market-monitoring framework established by Regulation (EU) No 1227/2011 on wholesale energy market integrity and transparency (REMIT). Future research could exploit more granular national datasets on renewable support schemes as comparable long-term European data become available. Finally, the estimated IMRs depend on a set of technical assumptions regarding plant efficiency, emission factors, residual-load thresholds, and the identification of marginal technology. Accordingly, the reported EIR and market-based transmission factors should be interpreted primarily in terms of their comparative patterns and orders of magnitude rather than as point estimates of the actual hourly pass-through or rents realised in individual electricity markets. Their use for regulatory calibration would require more granular market-specific analysis and sensitivity testing of the underlying technical parameters.

4. Results

The results are organised into subsections that progress from the determinants of renewable capacity expansion to the transmission of carbon costs to wholesale electricity prices.

4.1. Factors Associated with Renewable Capacity Development

The evidence in Table 4 indicates that renewable-energy investment decisions are predominantly policy-driven and that the EUA price signal alone is insufficient to drive capacity expansion, which is consistent with [17,18]. A 1% increase in subsidies is associated with a 0.28% increase in renewable capacity (M1), and this elasticity is statistically significant at the 5% level under country-clustered standard errors. The direction is consistent across the two-lag specification (see Appendix A Table A2 and the Driscoll–Kraay standard errors in Appendix A Table A3). The interaction term between lagged subsidies and the lagged EUA price is negative and weakly significant in M1 (−0.053, $p < 0.10$ under clustered SE), suggesting that the marginal effectiveness of subsidies declines as the carbon price increases—a result consistent with partial policy-overlap effects within the broader EU policy mix.

Table 4. Regression analysis of factors associated with renewable capacity development.

	M1: EUA	**M2: EUAREL**	**M3: EUA**
Subsidies	0.284 **	0.414	0.258 **
	(0.125)	(0.257)	(0.122)
EUA price	0.767		0.611
	(0.985)		(0.999)
Relative EUA price		−0.166	
		(0.700)	
Subsidies × EUA price	−0.053 *		−0.046
	(0.030)		(0.029)
Subsidies × Relative EUA price		−0.041	
		(0.031)	
Verified emissions (energy sector)	−0.037	−0.001	0.002
	(0.042)	(0.032)	(0.031)
GDP per capita	0.118	0.357	0.286
	(0.340)	(0.375)	(0.359)
Observations	306	295	295
Within R^2	0.114	0.112	0.115
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Clustered SE	Country	Country	Country
NO included	Yes	No	No

Source: the authors. * $p < 0.1$, ** $p < 0.05$. The standard errors are clustered at the country level (in parentheses). Within R^2 is computed after absorbing both country and year fixed effects (two-way demeaning). M1: EUA price, full sample (31 countries). M2: Relative EUA price (EUA/gas price), Norway excluded. M3: EUA price, Norway excluded. All regressors in logarithms; EUA price and subsidies lagged one period. The panel is unbalanced, with country-year coverage varying across specifications because of missing observations and transformations.

The within R^2 values (~0.11–0.12) reflect the explanatory power of the regressors net of both country and year fixed effects (two-way demeaning) and are therefore more conservative than conventional within-R^2 statistics that absorb only country effects. The overall fit of the full model, including fixed effects, exceeds 0.98, consistent with the high degree of country- and time-specific variation in renewable capacity.

The marginal effects shown in Figure 2 confirm these estimates. In all three specifications, the impact of energy subsidies is positive and statistically significant when the EUA price is low or intermediate. The marginal effect of subsidies declines progressively as carbon prices increase. In Model 1, the elasticity decreases from approximately 0.20 at the lowest EUA levels observed to 0.03–0.04 at the highest levels. A similar pattern emerges in Models 2 and 3, highlighting the robustness of the results across specifications.

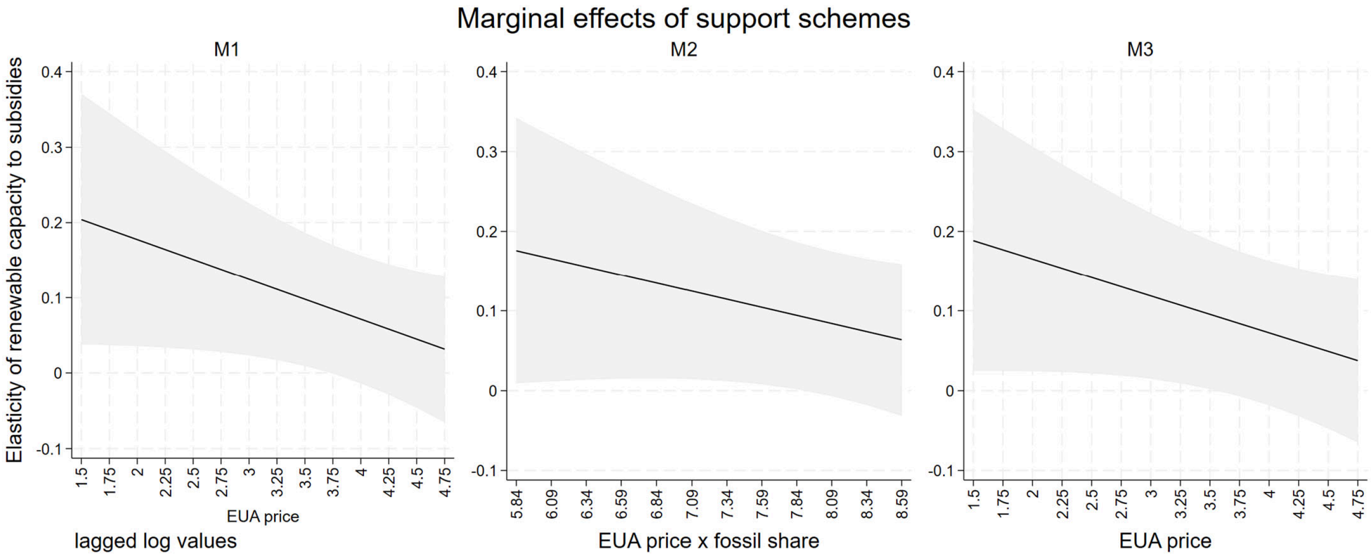

Figure 2. Marginal effects. Estimated marginal effects of renewable support schemes on installed renewable capacity for the three model specifications. The solid line represents the elasticity. Source: the authors.

From an economic perspective, these results suggest a partial overlap between the EU ETS price signal and the direct support mechanisms. When the carbon price is low, subsidies play a significant role in expanding the installed capacity. As EUA prices increase, part of this incentive is already provided indirectly through higher wholesale electricity prices and the improved competitiveness of low-emission technologies. Thus, the additional contribution of subsidies decreases, while it remains positive throughout the observed period. Overall, subsidies and carbon pricing neither operate as perfectly complementary instruments nor as complete substitutes; their interaction is better characterised as one of decreasing complementarity.

Diagnostic and robustness tests

The main variables exhibit pronounced upwards trends over the sample period. Panel unit-root tests, including the Fisher-ADF and Pesaran's CIPS tests, indicate that renewable capacity, the EUA price, and GDP are broadly consistent with integrated processes. In contrast, renewable-energy subsidies and verified emissions provide weaker evidence of nonstationarity. A panel Engle–Granger residual-based cointegration test does not reject the null hypothesis of no cointegration, suggesting that the estimated relationships should not be interpreted as long-term equilibrium elasticities.

To evaluate the sensitivity of the baseline specification, a first-difference model was estimated (see Appendix A Table A1 for details). Compared with the level specification, the first-differences model explains substantially less of the within-country variation, and the estimated subsidy coefficient changes its sign. This pattern is consistent with the distinction between the long-term policy effects on renewable deployment and short-term adjustment dynamics, supporting the use of level specifications as the primary empirical framework. Inference was further assessed using Driscoll–Kraay standard errors (Annex Table A3), which are robust to both temporal and cross-sectional dependence and produce qualitatively similar results while increasing the precision of the estimated subsidy and interaction effects. The overall conclusions remain unchanged. Potential cross-sectional dependence was examined using Pesaran's CD test. The null hypothesis of cross-sectional independence cannot be rejected, suggesting that the inclusion of year fixed effects adequately captures the main common shocks affecting MS during the sample period, including major EU ETS reforms, the COVID-19 pandemic, and the 2021–2022 energy crisis. Finally, because public support for renewable energy may be partially endogenous to national decarbonisation strategies, the estimated coefficients should be interpreted as conditional associations rather than as strict causal effects. The one-year lag applied to the policy variables mitigates concerns about contemporaneous reverse causality, although it does not fully eliminate endogeneity. An instrumental-variable strategy exploiting exogenous variation in the implementation of EU renewable-energy legislation represents a promising avenue for future research.

4.2. Survey Evidence

The survey results should be interpreted as descriptive evidence aimed at illustrating practitioners' perceptions of renewable-energy investment drivers. They complement the econometric analysis by providing qualitative insights into market expectations and perceived barriers rather than testing causal relationships. Regarding renewable energy generation projects, natural gas prices were the most influential driver, followed by long-term public support schemes lasting more than 10 years, regulatory stability, policy certainty, and structured procurement mechanisms. The EUA price recorded a lower average score. For energy storage systems, regulatory stability and policy certainty were the most important factors, followed by capital expenditure, subsidies, incentives, and development costs; in this case, the EUA price recorded an average value. Across both segments, respondents consistently attributed greater importance to subsidies, long-term support schemes, and regulatory stability than to the EUA price alone, confirming that market participants view public intervention and risk-reduction mechanisms as more decisive than carbon pricing alone [12,19].

For renewable energy generation projects, natural gas prices are the most influential factor, followed by regulatory stability and subsidies (Figure 3). Regarding storage projects, regulatory stability, capital investment, and subsidies receive the highest scores. Conversely, while still considered relevant, the price of EUAs consistently ranks below other key factors influencing investment in both generation and storage projects. These findings are consistent with those of previous studies that reported that market participants view public intervention and risk-reduction mechanisms as more decisive than carbon pricing alone [12,19]. However, the survey should be interpreted as providing exploratory evidence rather than statistically representative estimates of investor behaviour across the ETS. It forms part of an ongoing international research project, and the responses analysed in this study represent the first wave of the data collection. While the sample is purposively composed of professionals directly involved in renewable energy investment decisions across six major EU ETS countries, the findings are intended to complement the econometric analysis by providing practitioner-based insights into perceived investment drivers and barriers rather than supporting population-level inference.

4.3. Price-Setting Technologies and CPT

The application of the methodological framework confirms the existence of substantial IMRs across all countries analysed. The magnitude of estimated rents varies significantly: in 2022, Germany recorded €5.76 bn, France recorded €3.29 bn, Italy recorded €2.47 bn, Spain recorded €2.14 bn, Poland recorded €1.64 bn, the Netherlands recorded €0.89 bn, and Belgium recorded €0.38 bn; by 2024, values had been moderated to €2.10 bn (Italy), €1.48 bn (Germany), €0.96 bn (Spain), €0.88 bn (Poland), €0.86 bn (France), €0.40 bn (the Netherlands) and €0.13 bn (Belgium). Two elements are particularly relevant, as shown in Table 5. First, the magnitude of IMRs appears to be closely linked to the frequency with which gas-fired generation acts as the marginal technology rather than to the absolute level of the carbon price [30]. Second, the persistence of these rents over time indicates that the EU ETS-related component of electricity prices is not limited to temporary market conditions or exceptional scarcity episodes but represents a structural feature of electricity markets in which fossil technologies continue to play a central role in price formation [27,28]. Taken together, these results support the interpretation that one of the main observable effects of the EU ETS in the power sector operates through the price-formation channel and the associated generation of persistent IMRs.

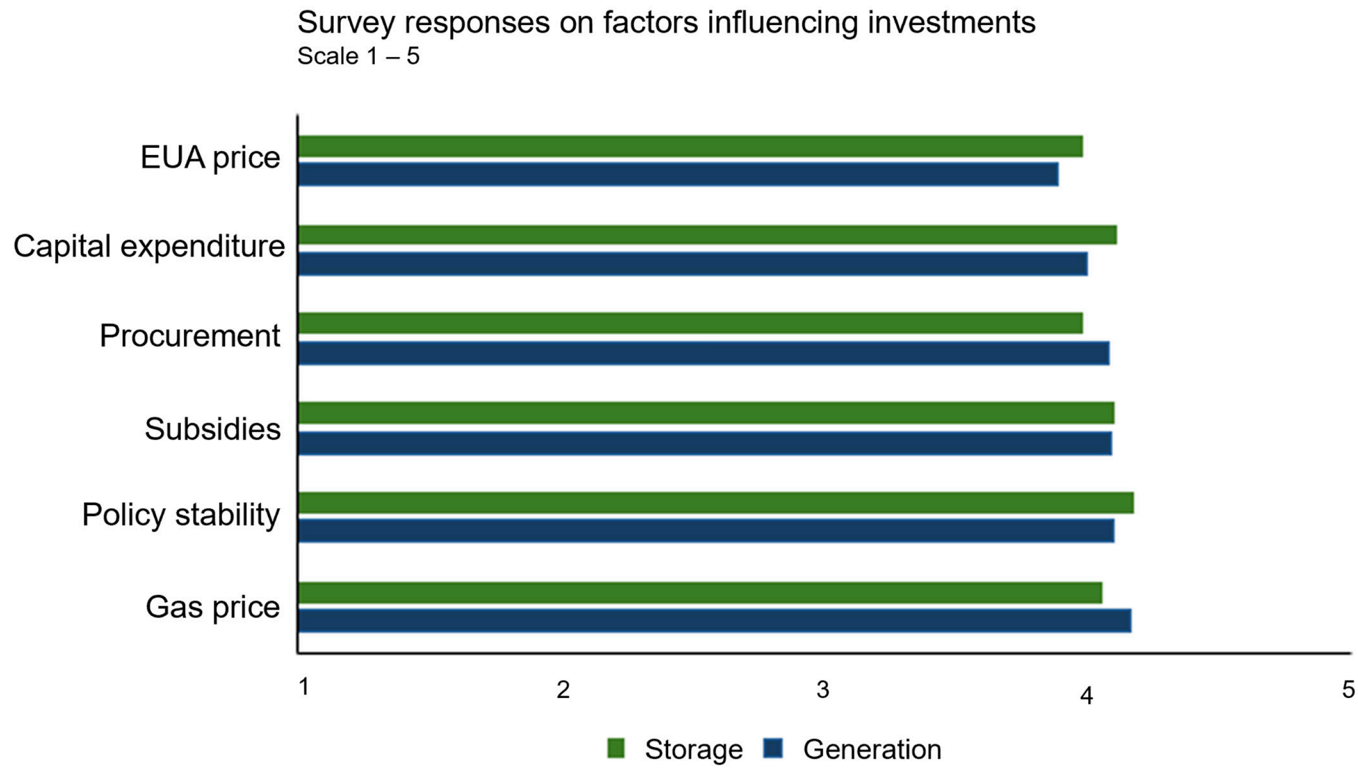

Figure 3. Factors influencing investment in generation and storage. The small differences in the numbers of observations reported for individual survey variables result from item-level non-response, if this is indeed the case. Source: the authors.

Table 5. Estimated EIR by country and year (€ billion, 2021–2024).

Country	2021	2022	2023	2024
Italy	1.66	2.47	2.28	2.10
Spain	1.99	2.14	1.43	0.96
France	1.71	3.29	1.78	0.86
Belgium	0.19	0.38	0.24	0.13
Germany	2.46	5.76	2.27	1.48
Poland	0.77	1.64	1.28	0.88
Netherlands	0.44	0.89	0.53	0.40

Source: authors' elaboration based on hourly ENTSO-E data, FactSet fuel prices (TTF gas and international coal benchmarks), and EEX EUA prices.

REF versus observed market-based factors

A comparison between the maximum regional CO_2 emission factors defined in Annex III of Commission Communication C/2026/196 [42]—used within the state aid framework for indirect EU ETS cost compensation—and the observed market-based factors derived from the empirical methodology reveals materially divergent magnitudes, as shown in Table 6. This divergence reflects the distinction between two different conceptual approaches: regulatory parameters rely on the structural characteristics of electricity systems (weighted average CO_2 intensity of fossil-based generation within predefined geographical areas), whereas market-based indicators measure the effective transmission of carbon costs into wholesale electricity prices through observed marginal price-setting conditions.

Table 6. Comparison between CO_2 emission factors and observed market-based factors (2021–2024).

Country	EU CO_2 Factor (tCO_2/MWh)	Observed Market-Based Factor	Reg./OBS. Ratio
Italy	0.44	0.36	1.2×
France	0.43	0.23	1.9×
Spain	0.47	0.21	2.2×
Germany	0.73	0.25	2.9×
Belgium	0.37	0.17	2.2×
Netherlands	0.44	0.27	1.6×
Poland	0.78	0.27	2.9×
Sweden	0.60	0.01	46.2×

Source: authors' elaboration based on hourly ENTSO-E data, FactSet fuel prices, EEX EUA prices, and Annex III of Commission Communication C/2026/196 (Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021). The factors in Annex III of C/2026/196 are the maximum applicable regional regions used to calculate the aid envelope under the indirect EU ETS cost compensation scheme. They are derived from structural averages of CO_2 intensity in fossil-based generation within predefined geographical areas and serve as compensation-relevant regulatory parameters. The market-based factors measure a different object: the effective transmission of carbon costs into wholesale prices under observed marginal price-setting conditions.

The results indicate that the EU ETS operates in the European power sector primarily as a wholesale-price transmission and inframarginal-rent generation mechanism, while subsidies and long-term contracts are also associated with capacity expansion. The estimated inframarginal-rent indicators are sizeable across the eight MS, while the comparison with REF suggests potentially relevant differences between structural regulatory parameters and the market-based indicators derived from our classification approach.

5. Discussion and Policy Implications

Our results contribute to the long-standing literature on the role of carbon pricing in driving low-carbon investment. Previous studies have reached mixed conclusions. Some have argued that under specific market and intermittency conditions, carbon taxes alone can weaken incentives for renewable investments or prove less effective than dedicated subsidies [24]. Others have shown that an EU ETS without recycling revenues into renewables may reduce renewable generation by reducing overall demand and increasing renewable costs, while using most EU ETS revenue to support all renewables can make the EU ETS important for renewable generation [10]. For the EU specifically, higher carbon prices have been shown to reduce the differences between subsidy types, although subsidies remain important alongside the EU ETS [37]. Another study has shown that higher permit volumes are associated with a lower share of renewables [20], and recent reviews stress that policy mixes combining subsidies, carbon pricing, green bonds, and other fiscal instruments are typically used in practice, with subsidies/FITs crucial for early deployment and carbon pricing becoming increasingly important as markets mature [19,22]. Our findings advance this literature. First, the econometric analysis suggests that subsidies remain the dominant driver of renewable capacity expansion and that the EUA price does not exhibit an independent effect on installed renewable capacity. These results are consistent with previous findings, suggesting that subsidies outperform other approaches [17]. The added value of our work lies in the triangulation between econometric, survey, and market-based evidence: the survey results corroborate the econometric findings from the perspective of market participants, while the estimation of IMRs provides a quantitative measure of the alternative channels through which the EU ETS operates in practice. Second, the estimation of the EIR extends previous analytical frameworks [25,26] to a more recent period (2021–2024) and a broader panel of eight MS, exploiting the granularity of ENTSO-E hourly data. The estimates seem to provide evidence consistent with a persistent price-formation channel, in line with recent evidence on gas as a marginal price-setter [28] and the role of the EPT [31,43]. The comparison between REF and observed market-based factors highlights an issue that has received limited attention in the literature. While the state aid framework for indirect compensation has been the subject of significant policy debate, the empirical extent of the divergence between structural and market-based indicators has rarely been systematically documented in the literature. The evidence developed here suggests that in several MS, the effective carbon cost CPT embedded in wholesale electricity prices may be materially lower than the maximum structural CO_2 emission factors used to define the compensation envelope. These findings have direct implications for the consistency of compensation schemes within the EU: a mechanism originally designed to mitigate distortions associated with carbon leakage risks could, under certain conditions, contribute to new forms of asymmetry if standardised structural parameters progressively diverge from observed market-based CPT dynamics as electricity systems decarbonise.

The EU ETS may simultaneously operate as a carbon-cost internalisation mechanism for fossil generation, a wholesale electricity price transmission mechanism, and an implicit revenue-transfer mechanism that generates persistent inframarginal revenues for low-carbon generation technologies that are not directly exposed to equivalent carbon costs. The coexistence of explicit support mechanisms financed by public resources and persistent EIRs may generate cumulative remuneration effects that are not fully captured in conventional assessments of EU ETS effectiveness and renewable energy support efficiency. The growing development of long-term contractual arrangements, together with the broader evolution of the European electricity market design framework under Regulation (EU) 2024/1747, reflects this structural transition toward a more differentiated relationship between short-term electricity price formation and long-term low-carbon investment remuneration [9]. Our findings also highlight the importance of developing assessment protocols to support the systematic evaluation of the effectiveness of national climate policies. In this respect, the exploratory cross-index assessment framework proposed by [44] represents a useful step toward improving the monitoring and comparison of climate policy instruments, including carbon pricing and fiscal policies.

Policy Implications

An effective decarbonisation policy should rely on the carbon price signal and consider its interaction with complementary instruments that provide investment certainty and support project bankability. The key policy challenge is to provide coherent short- and long-term signals for renewable-energy investments. The coexistence of explicit support schemes and persistent EIR calls for a more explicit assessment of cumulative remuneration effects, in line with the broader evolution of the European electricity market design framework under Regulation (EU) 2024/1747, which progressively encourages long-term contractual arrangements such as Contracts for Difference and Power Purchase Agreements as instruments capable of stabilising investor revenues without relying solely on short-term wholesale price signals. The divergence between the REF defined in Annex III of Commission Communication C/2026/196 and the market-based indicators derived from analysis points to a potential issue for the design of the state aid framework for indirect EU ETS cost compensation. Given the stylised nature of the identification procedure, these estimates should not be interpreted as precise measures of the actual carbon cost pass-through in individual markets. Rather, they indicate that in several MS, effective market-based transmission may differ from the structural CO_2 emission factors used to define the compensation envelope. This suggests that compensation schemes calibrated exclusively to structural averages may warrant periodic comparison with observed market dynamics as electricity systems continue to decarbonise.

The indicators developed in this study aim to identify potential divergences that may warrant a more detailed market-specific assessment. Such monitoring can help assess whether structural compensation factors remain representative as electricity systems progressively decarbonise. Taken together, these implications indicate that the effectiveness of the EU ETS in the power sector should be assessed by distinguishing between three transmission channels: carbon-cost internalisation in fossil generation, wholesale electricity-price transmission, and implicit revenue redistribution to low-carbon technologies. The next phase of EU ETS reform should be jointly assessed with the calibration of complementary support schemes and indirect compensation rules, recognising that the carbon price signal transmitted to industrial and electricity consumers reflects the interaction between regulatory scarcity, electricity market design, and the broader architecture of public support instruments. Future policy should focus on both carbon pricing and electricity market designs specifically tailored to renewable energy systems that provide stable investment signals, integrate flexibility technologies, and support the transition toward low-carbon electricity markets [45]. Clearly, remarkable differences exists in countries in terms of energy systems, transition pathways, policy mixes, and investment conditions. Indeed, previous research shows that European energy transitions remain strongly country-specific and that differences in factors such as policy design, technological structures, and financing conditions can influence renewable deployment [46,47]. Future research should therefore examine more explicitly how these national contexts shape investors' perceptions and the interaction between carbon pricing and renewable-energy support.

6. Conclusions

This study evaluated the evolution of renewable energy development in Europe by integrating panel econometric analysis, an international survey of market participants, and market-based estimation of IMRs. The evidence indicates that targeted subsidies are directly associated with renewable capacity expansion and that the EU ETS is an important component of the policy framework, operating through the carbon price signal, wholesale electricity price formation, and generation of inframarginal revenues. These findings point to distinct but interacting transmission channels rather than a simple substitution between carbon pricing and renewable support policies. Therefore, a more effective policy framework should coordinate carbon pricing, electricity market design, and targeted renewable support while accounting for their interactions and changing market conditions. Strengthening long-term investment certainty, project bankability, and the coherence of these instruments can enhance the effectiveness of the policy mix and support a faster transition to renewable energy.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. First-differences robustness.

	M1	M2	M3
Δ Subsidies	−0.053 *	−0.051 **	−0.054 **
	(0.027)	(0.021)	(0.026)
Δ EUA price	−0.183		−0.173
	(0.169)		(0.180)
Δ Relative EUA price		−0.309	
		(0.296)	
Δ Subsidies × Δ EUA price	0.149		0.162 *
	(0.094)		(0.094)
Δ Subsidies × Δ Rel. EUA price		0.172 **	
		(0.082)	
Δ Verified emissions	−0.021	−0.005	−0.008
	(0.018)	(0.010)	(0.012)
Δ GDP per capita	0.201	0.279	0.245
	(0.129)	(0.194)	(0.209)
Observations	302	291	291
Within R^2	0.028	0.039	0.031
Country FE	No	No	No
Year FE	Yes	Yes	Yes
Clustered SE	Country	Country	Country
NO included	Yes	No	No

* $p < 0.1$, ** $p < 0.05$. The standard errors are clustered at the country level in parentheses. All variables in the first differences (Δ). Year fixed effects included; country FE omitted (FD removes country heterogeneity).

Table A2. Two-period lag robustness.

	M1: (Lag 2)	M2: (Lag 2)	M3: (Lag 2)
Subsidies	0.303 **	0.554 **	0.299 **
	(0.116)	(0.260)	(0.119)
EUA price	1.042		1.020
	(0.787)		(0.824)
Relative EUA price		0.435	
		(0.740)	
Subsidies × EUA price	−0.063 **		−0.059 **
	(0.028)		(0.028)
Subsidies × Relative EUA price		−0.060 *	
		(0.032)	
Verified emissions (energy sector)	−0.016	0.028	0.034
	(0.058)	(0.035)	(0.034)
GDP per capita	0.222	0.258	0.318
	(0.327)	(0.380)	(0.361)
Observations	278	268	268
Within R^2	0.119	0.134	0.137
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Clustered SE	Country	Country	Country
Lag order	2	2	2
NO included	Yes	No	No

* $p < 0.1$, ** $p < 0.05$. The standard errors are clustered at the country level in parentheses. All regressors in logarithms; key regressors lagged for two periods.

Table A3. Driscoll–Kraay Standard Errors.

	M1	M2	M3
Subsidies	0.284 ***	0.414 ***	0.258 ***
	(0.047)	(0.066)	(0.054)
EUA price	0.767**		0.611 *
	(0.357)		(0.358)
Relative EUA price		−0.166	
		(0.407)	
Subsidies × EUA price	−0.053 ***		−0.046 ***
	(0.007)		(0.010)
Subsidies × Relative EUA price		−0.041 ***	
		(0.007)	
Verified emissions (energy sector)	−0.037	−0.001	0.002
	(0.049)	(0.045)	(0.045)
GDP per capita	0.118	0.357	0.286 **
	(0.139)	(0.224)	(0.134)
Observations	306	295	295
Within R^2	0.114	0.112	0.115
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
SE type	Driscoll–Kraay	Driscoll–Kraay	Driscoll–Kraay
NO included	Yes	No	No

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Driscoll–Kraay standard errors (L = 1) in parentheses, consistent under general cross-sectional and temporal dependence.

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