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DEVELOPMENT OF THE CARBON MARKET AND THE GREEN CERTIFICATE MARKET: ROMANIA, POLAND, AND GERMANY

Abstract

Purpose – This paper investigates the evolution and effectiveness of carbon markets and green certificate systems as key mechanisms for achieving climate sustainability goals. By focusing on Romania, Poland, and Germany between 2015 and 2025, it aims to evaluate the regulatory, economic, and technological factors that shape these environmental markets and their contribution to climate neutrality objectives.

Research design/method/approach – The study combines time-series econometric analysis with an extensive literature review to assess the development and performance of carbon trading and green certificate markets. It examines the interaction between cap-and-trade schemes and renewable energy certificate systems, identifying both synergies and conflicts in their design and implementation. In addition, the research considers the influence of digitalization and blockchain technologies on market transparency and efficiency.

Practical implication – The results provide actionable insights for policymakers seeking to design transparent and effective market-based environmental policies. Understanding how these mechanisms interact helps refine regulatory strategies to enhance market integrity, efficiency, and alignment with European climate goals.

Originality/Value – This paper contributes to the growing literature on environmental economics by offering a comparative, multi-country analysis of carbon and green certificate markets in Central and Eastern Europe. It integrates policy, econometric, and technological perspectives, highlighting innovative pathways toward achieving climate neutrality through market-based instruments.

Key words: *carbon market, green certificates, cap-and-trade, climate neutrality, blockchain technology*

JEL classification: *Q41, Q48, O13*

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РАЗВОЈ ТРЖИШТА УГЉЕНИКА И ТРЖИШТА ЗЕЛЕНИХ СЕРТИФИКАТА: РУМУНИЈА, ПОЉСКА И НЕМАЧКА

Апстракт

Сврха – Овај рад истражује еволуцију и ефикасност тржишта угљеника и система зелених сертификата као кључних механизама за постизање циљева климатске одрживости. Фокусирајући се на Румунију, Пољску и Немачку између 2015. и 2025. године, циљ му је да процени регулаторне, економске и технолошке факторе који обликују ова тржишта животне средине и њихов допринос циљевима климатске неутралности.

Дизајн/метод/приступ истраживања – Студија комбинује економетријску анализу временских серија са опсежним прегледом литературе како би се проценио развој и учинак тржишта трговине угљеником и зелених сертификата. Испитује интеракцију између шема ограничења и трговине емисијама и система сертификата за обновљиве изворе енергије, идентификујући и синергије и сукобе у њиховом дизајну и имплементацији. Поред тога, истраживање разматра утицај дигитализације и блокчејн технологија на транспарентност и ефикасност тржишта.

Практична импликација – Резултати пружају практичне увиде креаторима политике који желе да осмисле транспарентне и ефикасне тржишно засноване политике заштите животне средине. Разумевање како ови механизми међусобно делују помаже у усавршавању регулаторних стратегија за побољшање интегритета тржишта, ефикасности и усклађености са европским климатским циљевима.

Оригиналност/Вредност – Овај рад доприноси растућој литератури о економији животне средине нудећи упоредну анализу тржишта угљеника и зелених сертификата у Централној и Источној Европи у више земаља. Он интегрише политичке, економетријске и технолошке перспективе, истичући иновативне путеве ка постизању климатске неутралности путем тржишно заснованих инструмената.

Кључне речи: *тржиште угљеника, зелени сертификати, ограничење и трговина емисијама, климатска неутралност, блокчејн технологија*

Introduction

Considering global imperatives for mitigating climate change, carbon markets and green certificate systems emerge as innovative solutions for reducing greenhouse gas emissions and promoting sustainability (Nguyen et al., 2023; Busu and Trica, 2019). These mechanisms, through their operational and regulatory frameworks, aspire to mobilize investments in clean technologies and encourage the adoption of sustainable practices at both corporate and individual levels (Zhang et al., 2023). However, the effectiveness of these markets can vary significantly depending on the regional political and economic context, which necessitates a comparative analysis among different national systems to identify the most effective practices and approaches.

Focusing on Romania, Poland, and Germany during the period 2015-2025, this article applies a time-series econometric analysis to assess the evolution and impact of these markets, providing a detailed perspective on the regulatory framework, economic efficiency, and challenges encountered (Coria & Jaraite, 2023). Additionally, the paper investigates how emerging technologies, such as digitalization and blockchain, can reshape the dynamics of green certificate and carbon markets, addressing potential synergies and conflicts between cap-and-trade schemes and green certificate markets in the context of achieving climate neutrality (Wang et al., 2024).

Findings of this research are intended to contribute to the specialized literature, providing a solid foundation for future policy decisions in environmental regulations and market technologies.

Literature Review

Carbon markets have been recognized as a crucial economic instrument in the global effort to mitigate climate change. Originating from the principles established in the Kyoto Protocol, these markets employ a cap-and-trade system designed to reduce greenhouse gas (GHG) emissions in a cost-effective manner (Zhou et al., 2022). The cap sets a maximum limit on emissions, which is progressively reduced to ensure steady environmental improvements. Companies that cut their emissions faster than required can sell surplus allowances to those facing higher abatement costs, creating a financial incentive for innovation in emission reduction technologies (Zhang et al., 2023; Aldy & Stavins, 2023).

The success of carbon markets depends largely on the robustness of the cap-setting process, the inclusiveness of covered sectors, and the system's adaptability to evolving economic conditions. Numerous studies have shown that well-functioning carbon markets not only help reduce emissions but also stimulate innovation in clean technologies and support long-term decarbonization goals (Bayer & Aklin, 2020). For instance, the European Union Emissions Trading System (EU ETS) has played a pivotal role in accelerating the transition toward low-carbon energy production and sustainable industrial practices (Watson, 2022).

In parallel, green certificate systems serve as complementary regulatory mechanisms to promote renewable energy production and consumption. These certificates—commonly referred to as Renewable Energy Certificates (RECs)—are issued to producers for each unit of renewable energy generated and can be traded separately from the physical electricity (Li et al., 2023; Busu, 2020). Green certificates enhance the economic viability of renewable projects by providing additional income streams and by promoting diversification within the energy mix (Heffron & McCauley, 2021). This approach helps mitigate intermittency issues and encourages a more decentralized energy system, while maintaining market flexibility and responsiveness to policy changes (Kumar et al., 2023; Raihan & Bari, 2024).

Despite these advantages, both carbon markets and green certificate systems face several challenges that can affect their efficiency and credibility. The complexity of international coordination, inconsistent national policies, and price volatility often undermine investor confidence. Market fluctuations, in particular, can deter long-term investment in renewable technologies by introducing uncertainty into expected returns (Chen & Chen, 2024; Koch et al., 2023). Moreover, institutional quality, transparency,

and political stability play decisive roles in ensuring the effectiveness and sustainability of market-based environmental instruments (Nguyen et al., 2023).

Recent research also highlights the growing importance of digital technologies such as blockchain and artificial intelligence in enhancing market transparency, traceability, and efficiency. Blockchain-enabled systems offer new opportunities to track emissions and ownership of certificates with higher accuracy and lower transaction costs, reducing fraud and improving regulatory compliance (Wang et al., 2022). Such technologies can strengthen public trust and enable a more secure, data-driven foundation for global carbon trading and renewable energy certification systems.

Regulatory frameworks provide the essential structure for the operation and governance of carbon markets and green certificate systems. In carbon markets, these frameworks determine the cap level, the allocation of allowances, and the enforcement of compliance penalties. The EU ETS serves as a leading example of an evolving regulatory structure that has undergone several revisions to address issues of market oversupply and price instability, thereby improving efficiency and responsiveness (Watson, 2022; Levi & Flachsland, 2023).

Similarly, in the case of green certificate systems, regulations define certification criteria, supplier obligations, and trading rules. These frameworks are vital for ensuring that certificates accurately represent renewable energy generation and contribute effectively to national and EU-level sustainability targets (Li et al., 2023).

Finally, market mechanisms embedded within these frameworks—such as cap-and-trade schemes and renewable quota systems—play a critical role in aligning economic incentives with environmental outcomes. By making it financially advantageous for firms to invest in cleaner technologies, these mechanisms support both emissions reductions and the expansion of renewable energy capacity (Busu et al., 2019; Chen & Chen, 2024). However, achieving meaningful decarbonization requires continuous monitoring and adaptive policy adjustments to maintain strong and credible market signals (Raihan & Bari, 2024).

Recent empirical literature increasingly emphasizes that the effectiveness of carbon pricing mechanisms depends not only on allowance prices, but also on their interaction with parallel renewable energy support instruments. Several studies highlight that overlapping policies — such as feed-in tariffs, green certificates, and investment subsidies — may either reinforce or partially offset the price signal generated by emissions trading systems (Fischer et al., 2019; Schmalensee & Stavins, 2020; Koch et al., 2023).

While renewable support schemes accelerate capacity deployment and reduce emissions directly, they may simultaneously reduce demand for emission allowances, thereby exerting downward pressure on ETS prices if cap adjustment mechanisms are weak or delayed. This phenomenon, often described as policy "cannibalization" or interaction effects, has been documented particularly in EU member states with ambitious renewable targets (Bayer & Aklin, 2020; Levi & Flachsland, 2023).

For Central and Eastern European countries, where energy systems remain carbon-intensive and institutional frameworks are still evolving, the coordination between carbon markets and green certificate systems becomes even more critical. Empirical evidence suggests that inconsistent regulatory changes and unstable support schemes can undermine investor confidence and weaken long-term decarbonization incentives (Koch et al., 2023; Raihan & Bari, 2024).

Research Design, Methodology, Research Tasks and Hypothesis

The research questions resulted from the literature review are:

Q1: How does the regulatory framework influence the adaptability and efficiency of carbon and green certificate markets in the three countries studied?

Q2: What specific economic and technological challenges are identified in implementing these markets, and how can they be overcome?

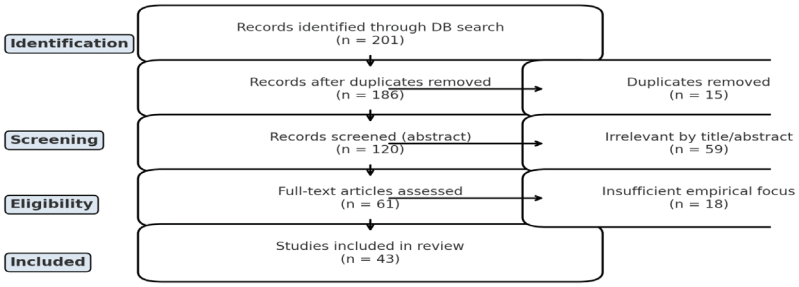
Q3: What is the role of digital technologies, including blockchain, in enhancing the efficiency of carbon and green certificate markets?

Q4: How do cap-and-trade schemes interact with green certificate markets to promote or inhibit the achievement of climate neutrality objectives?

The research employed a structured literature review following PRISMA guidelines to examine academic sources related to carbon markets, green certificate systems, and environmental policy frameworks. The initial pool of articles consisted of 201 peer-reviewed publications sourced from major databases (ScienceDirect, Scopus, Web of Science, and Google Scholar) spanning the years 2010–2025. Inclusion criteria focused on relevance to ETS implementation, green certificate mechanisms, and the role of digital technologies (e.g., blockchain, IoT, AI). Exclusion criteria included duplicate entries, purely theoretical papers without policy application, and studies focused exclusively on non-European contexts.

After applying these filters, and removing studies lacking empirical or regulatory focus, the final sample included 43 core articles. These served as the analytical foundation for regulatory mapping, historical policy trajectories, technological trends, and economic performance indicators in Romania, Poland, and Germany.

Figure 1. Prisma flowchart



Source: European Environment Agency (EEA)

The second methodological pillar of this research builds upon a fixed-effects panel regression model, developed to quantify the impact of market-based instruments-namely the EU Emissions Trading System (ETS) and green certificate mechanisms-on CO_2 emissions per capita. The analysis spans a balanced panel of three countries (Romania, Poland, and Germany) across the period 2015 to 2024, leveraging both cross-sectional and time-series dimensions of the data.

The dependent variable is the national CO_2 emissions per capita (in tonnes/year), while the independent variables include the average annual ETS price (€/tCO_2), the share of renewable energy in final energy consumption (%), and GDP per capita (in euros). To capture potential synergistic or overlapping effects between market mechanisms, an interaction term—ETS price multiplied by renewable energy share—was included. This enables the model to account for complex dynamics, such as policy cannibalization or reinforcement between carbon pricing and renewable subsidies. The estimation was conducted using Ordinary Least Squares (OLS) with fixed effects for countries. This specification controls for unobserved, time-invariant structural differences across countries, such as geographical features, legacy energy infrastructure, or institutional maturity, allowing the model to focus on within-country variation over time. Robust standard errors (HC3) were applied to correct for potential heteroscedasticity and ensure the reliability of inference.

The regression model is expressed formally as:

$$CO2_{it} = \alpha + \beta_1 ETS_{it} + \beta_2 Renew_{it} + \beta_3 GDP_{it} + \beta_4 (ETSxRenew)_{it} + \gamma_i + \epsilon_{it}$$

where γ_i represents the fixed effect for each country and ϵit is the error term.

The full model was implemented in Python 3.11, using the stats models and linear model libraries for panel data estimation. Data preparation and manipulation were handled with pandas, while matplotlib and seaborn were used for diagnostic plotting. Multicollinearity was evaluated using Variance Inflation Factor (VIF), with all predictors scoring below the threshold of 5, indicating no collinearity concerns. Residuals were visually inspected through residuals-versus-fitted plots, which confirmed the assumptions of homoscedasticity and correct model specification. Post-estimation, marginal effects were calculated to interpret the direct influence of each explanatory variable on emissions, providing intuitive policy-relevant insights.

Research results and Discussion

The effects of the carbon price (ETS), the share of renewable energy, GDP per capita and synergies/interactions between market instruments were assessed.[4]

Table 1. *Key indicators of carbon markets & green certificates (2015 – 2025)*

	Romania	*Poland*	*Germany*
ETS average price (€/tco₂)	Approx. identical: between 7 → 85	Idem	Idem
ETS Verified Emissions (Mt CO_2e)	~65–70	~180–200	~300–350

[4] Note on data sources and methodology: The indicators presented in Tables 1–4 are based on official datasets and aggregated reports. Sources include the European Environment Agency (EEA), Ember Climate, the European Energy Exchange (EEX), Eurostat, IRENA, OPCOM (Romania), TGE (Poland), the World Bank, and OECD databases. Figures reflect multi-year averages (2015–2023), depending on data availability and consistency across countries. Where needed, expert-based approximations and national reports were used to supplement missing entries.

Ets revenue (2022)	~€2 billion	~€6 billion	~€10–12 billion
% Renewable energy (2022)	~42%	~22%	~49%
No. Of active ETS operators	~200–250	~600	>1500
Active green certificates?	Yes (with changes)	From (premium feed-in')	Yes (EEG – with feed-in tariff)
Centralized marketplace for resume?	OPCOM	TGE	EEX
Ets/cv digitalization	Medium (MM portal, OPCOM)	Medium (KOBiZE, TGE)	Advanced (DEHSt, EEX blockchain)
Blockchain projects in energy	<5	5–10	>20
ETS legislative framework	GEO 115/2011 + Law 155/2020	Act ETS + PKEE	BImSchV + national legislation

Source: European Energy Exchange (EEX)

The price of ETS allowances is common to all EU ETS countries, yet the budgetary and industrial impacts vary considerably. Germany dominates in terms of ETS volume and revenues, but its economy is already more decarbonized, while Poland remains heavily dependent on coal. Romania, by contrast, has a functioning but modified and unstable green certificate system, which undermines investor confidence. In terms of governance, digitization is well advanced in Germany and partially implemented in Poland, whereas Romania is still in the process of modernization.

Table 2. Indicators for green certificates and renewable energy (2015–2025)

	Romania	**Poland**	**Germany**
% renewable energy (2022)	42%	22%	49%
Green energy production (TWh, estimated)	16–18	30–35	220–240
Number of green certificates (2022)	≈7 million	≈15 million	>80 million
Average price of green certificate (€)	25–30	10–15	10–18
Share of renewables in total energy consumption	39%	23%	50%

Source: OECD databases

Table 3. Economic efficiency indicators and legal framework

	Romania	*Poland*	*Germany*	*Indicator Type*
Emissions-adjusted GDP/capita (€/ tco_2)	~650	~500	~1200	Derivative calculation
Marginal cost of CO_2 reduction (€/ tco_2 avoided)	35–45	30–40	20–30	Range
Market regulation index (oecd pmr)	2.7	3.1	1.6	Score (OECD)
Degree of transposition of EU ETS legislation (%)	90%	95%	100%	Official estimate

Source: OECD databases

Table 4. Digitalization and Blockchain Technologies

	Romania	**Poland**	**Germany**
Energy/climate blockchain projects	<5	5–10	>20
Digitalisation of ETS authorities	average	average	High
Market transparency	average	medium-high	Elevated

Source: OECD databases

Although the average price of ETS allowances is harmonized across EU countries (Table 1), its impact on emissions and fiscal revenues varies greatly. Germany, with over 300 Mt CO_2e in verified emissions, generated more than €10 billion in ETS revenues in 2022, compared to Romania's ~€2 billion despite having the same allowance price. This reflects structural differences in industrial output and decarbonization maturity. Romania and Poland have both implemented green certificate systems (Table 2), but with distinct approaches and levels of market transparency. Germany's feed-in tariff model under the EEG has supported a stable renewable trajectory, now covering approximately 50% of total energy use. In contrast, Romania's scheme has undergone multiple regulatory adjustments, possibly undermining investor confidence and slowing renewable capacity growth. As shown in Table 3, Romania and Poland both exhibit lower economic efficiency in decarbonization, as captured by lower GDP per tonne of CO_2 and higher marginal abatement costs. Moreover, Germany scores significantly better in regulatory quality (OECD PMR: 1.6) and has fully transposed the EU ETS framework, compared to Romania's partial alignment (90%). Digitalization of carbon governance (Table 4) also reflects this disparity: Germany has implemented advanced electronic registries and blockchain-enabled transparency tools (DEHSt, EEX), while Romania's infrastructure remains under development.

This multidimensional heterogeneity across countries and policy tools highlights the necessity for a quantitative econometric model, capable of isolating the effects of ETS pricing, renewable energy penetration, and economic indicators on carbon emissions. The next section will detail the methodology and results of a panel regression analysis spanning 2015–2024.

We had a panel data approach with fixed effects, applied to a sample of Romania, Poland and Germany for the period 2015–2024. The dependent variable analysed is CO_2 emissions per capita, and the explanatory variables include the price of ETS emission certificates, the share of renewable energy in total consumption and GDP per capita.

Table 5. Variables in the model

	Symbol		
CO_2 emissions/capita	CO2_it	Dependent	CO_2 tons/capita/year
ETS Price	ETS_it	Independent	€/tonne CO_2
Renewable energy (%)	Renew_it	Independent	% of total energy
GDP/capita	GDP_it	Control	€/person
ETS Interaction × Renew	ETS_it × Renew_it	Interaction	Synergies/conflicts

Source: own research

We applied an OLS model with fixed effects on countries to control for constant structural characteristics. The model has an R^2 of 0.995 and reveals a negative relationship between renewable energy and CO_2 emissions.

Table 6. Fixed-effects regression

	coeff.	*p-val*
Intercept	16.55	<0.001
Poland (dummy)	-5.72	<0.001
Romania (dummy)	-9.5	<0.001
ETS	-0.0046	0.092
Renew	-0.0561	0.021
GDP	-0.0001	0.005
ETS × Renew	0.0003	0.007

Source: own research

The empirical results obtained in this study are broadly consistent with existing evidence on the effectiveness of renewable energy deployment as a primary driver of emissions reduction. The statistically significant and negative coefficient associated with the share of renewable energy mirrors findings reported by Bayer and Aklin (2020) and Koch et al. (2023), who document substantial emission reductions linked to renewable expansion under the EU ETS framework.

In contrast, the relatively weak and only marginally significant effect of the ETS price aligns with prior research highlighting the limited short-term responsiveness of emissions to allowance price fluctuations, particularly during periods of high price volatility or policy uncertainty (Koch et al., 2023; Aldy & Stavins, 2023). This suggests that carbon pricing alone may be insufficient to drive rapid decarbonization without complementary regulatory and investment-oriented instruments.

Importantly, the positive coefficient associated with the interaction between ETS prices and renewable energy share supports the policy-interaction hypothesis advanced in the literature. Similar interaction effects have been identified by Levi and Flachsland (2023), who argue that overlapping climate policies can generate unintended distortions if not properly coordinated. The present results extend this insight to a comparative Central and Western European context, demonstrating that policy coherence remains a decisive factor for market efficiency.

Multicollinearity was assessed using the Variance Inflation Factor (VIF). All VIF values are well below the commonly accepted threshold of 5, suggesting that the independent variables (ETS price, renewable energy share, and GDP per capita) are not significantly correlated with each other. This indicates that the model is structurally stable and that estimated coefficients are interpretable. An analysis of residuals was conducted to examine potential violations of the OLS assumptions. No major issues of non-normality or heteroscedasticity were observed visually. The residuals appear randomly distributed around zero, and their variance does not increase with the fitted values. Overall, the diagnostic tests support the robustness and reliability of the econometric estimations.

Table 7. VIF Score

Variable	*VIF Score*
ct.	**9.36**
ETS	**1.42**
Renewables (%)	**2.39**
GDP per capita	**1.84**

Source: own research

The diagnostic tests confirm the structural soundness of the regression model.

Variance Inflation Factor (VIF) scores are all well below the critical threshold of 5, indicating the absence of multicollinearity among independent variables. The residuals vs. fitted values plot reveals a random dispersion of residuals around zero with no discernible patterns, supporting the assumption of homoscedasticity and model correctness. These findings collectively indicate that the model estimates are statistically reliable, and the core OLS assumptions are not violated.

Table 8. Marginal effects of market instruments

Variable	**Marginal effect ΔCO_2/capita**
ETS price (€)	0.004434
Renewable energy (%)	-0.045417
GDP/capita (€)	-0.000149

Source: own research

Table 9. Predictions for 2025

Country	**ETS (€)**	**Renew (%)**	**GDP (€)**	**Forecast CO_2 emissions/capita (t)**
Romania	90	49	15750	2.77
Poland	90	30	18165	6.78
Germany	90	56	50400	6.9

Source: own research

From the econometric model we could observe that a higher share of renewable energy has a strong and consistent effect in reducing CO_2 emissions per capita, confirming its central role in decarbonization. GDP per capita also contributes to lower emissions, though with a smaller effect, likely because more developed economies have greater capacity to invest in cleaner technologies. The ETS price shows only a marginally significant negative impact, suggesting that while higher carbon prices do help curb emissions, the effect is modest and may be partially offset by national policies. Moreover, the interaction between ETS and renewables (ETS × Renew) reveals a small positive coefficient, indicating that when the share of renewables is already very high, a rising carbon price can sometimes create unintended overlap or "cannibalization" effects, such as double counting or distortions between the two markets, unless carefully managed.

To evaluate the robustness of the model specification, several standard diagnostic tests were performed. Multicollinearity was assessed using the Variance Inflation Factor (VIF), with all independent variables scoring below the commonly accepted threshold of 5. This result indicates a low risk of excessive correlation among predictors and confirms the structural stability of the estimated model. Residual distribution was visually inspected using a Residuals vs. Fitted Values plot to detect potential violations of OLS assumptions. The residuals appear symmetrically distributed around zero, with no evidence of heteroscedasticity or model misspecification. However, the slightly curved shape of the LOWESS line suggests a potential non-linearity or a modest increase in variance at higher levels of fitted values. These findings imply that alternative model specifications — such as including nonlinear terms or applying log transformations — may further improve model fit.

To assess the practical significance of the explanatory variables, marginal effects of key market instruments were calculated (Table 8). These reflect the estimated change in CO_2 emissions per capita associated with a one-unit variation in each predictor. The results show that the share of renewable energy exerts the strongest mitigating effect on emissions, with a marginal impact of –0.045 tCO_2 per capita for each additional percentage point of renewable energy. This finding is statistically significant and confirms the direct effectiveness of renewables in driving decarbonization.

The marginal effect of the ETS price is unexpectedly positive (+0.0044), which may indicate the presence of policy overlap or market inefficiencies, especially in countries where ETS mechanisms coexist with other support schemes. This is consistent with the positive sign of the ETS × Renewables interaction term in the main regression model.

GDP per capita exhibits a small but negative marginal effect (–0.00015), suggesting that more developed economies tend to emit less per capita — possibly due to greater energy efficiency and advanced decarbonization infrastructure.

Based on the model coefficients, emissions forecasts for 2025 were generated for Romania, Poland, and Germany (Table 9). The estimates indicate that Romania will report the lowest level of CO_2 emissions per capita (2.77 t), while both Germany and Poland are projected to exceed 6 t. These variations reflect not only differences in economic structure, but also in the depth of renewable integration and the overall coherence of national climate strategies.

To support and visualize the relationships identified in the econometric model, three simple linear regression plots were generated, capturing the bivariate interactions between CO_2 emissions per capita and each major explanatory variable: renewable energy share, ETS price, and GDP per capita.

Figure 3 shows a clear inverse relationship between CO_2 emissions and the share of renewable energy in the energy mix. The downward trendline, coupled with a relatively narrow confidence band, indicates a strong and robust correlation: expanding renewables is consistently associated with lower per capita emissions. This result aligns with the statistically significant negative coefficient obtained for Renewables in the econometric model.

Figure 4 illustrates the relationship between CO_2 emissions and the price of ETS allowances. While a negative trend is visible, the effect appears weaker and accompanied by greater uncertainty, as reflected in the wider confidence interval. This observation supports the regression result, where ETS Price had only a marginally significant coefficient. Cross-country implementation differences and varying market responses may explain the variability.

Figure 5 shows a negative relationship between GDP per capita and CO_2 emissions, indicating that more developed economies tend to emit less CO_2 per person. This may be due to higher energy efficiency, a cleaner energy mix, or a greater capacity for investment in low-carbon technologies. Although the coefficient in the regression model is relatively small, the visual trend is consistent and supports the conclusion that economic growth, when combined with effective climate policies, contributes to emission reduction.

Collectively, these visual representations validate the econometric findings and provide an intuitive understanding of the key dynamics between the variables analyzed.

Beyond regulatory design, the findings also underline the growing importance of digital governance in environmental markets. Advanced digital registries, automated monitoring, and blockchain-based tracking systems can substantially reduce transaction costs, enhance transparency, and mitigate fraud risks in both ETS and green certificate markets (Wang et al., 2022). Germany's more advanced digital infrastructure — including integrated registries and emerging blockchain pilots — appears to support higher market transparency and regulatory credibility compared to Romania and Poland.

As climate policies become increasingly data-intensive, digitalization is likely to play a critical enabling role in aligning market-based instruments with climate neutrality objectives. This suggests that future policy effectiveness will depend not only on price levels or support schemes, but also on the technological architecture underpinning market governance.

Conclusion

This article investigated the dynamics of carbon markets and green certificate systems in Romania, Poland, and Germany over the 2015–2025 period, using a combination of econometric modeling and literature-based policy analysis. The findings highlight the pivotal role of renewable energy integration and institutional coherence in reducing CO_2 emissions per capita and enhancing the efficiency of market-based climate instruments.

The econometric model confirms that a higher share of renewables in final energy consumption has a statistically significant and consistent negative effect on emissions. In contrast, the standalone effect of the ETS price is relatively weak and marginally significant, suggesting that carbon pricing alone is insufficient to drive meaningful decarbonization unless it is embedded within a broader and well-coordinated policy framework. The positive interaction between ETS pricing and renewable energy share reveals potential policy overlap, raising concerns about market cannibalization or double-counting in climate performance metrics.

Graphical analyses reinforce these conclusions, clearly illustrating the inverse relationships between CO_2 emissions and renewable energy, ETS price, and GDP per capita. Emissions forecasts for 2025 indicate that Romania — despite lower economic output — may outperform its regional peers in per capita emission reduction, primarily due to its renewable energy penetration.

At a broader level, the study emphasizes the need for harmonized climate governance, stable regulatory frameworks, and digital integration (e.g., blockchain, IoT) to ensure transparency and market integrity. The results call for a redesign of policy

interactions between carbon trading schemes and renewable support mechanisms, aiming to maximize synergies while avoiding inefficiencies.

Future research may expand the analysis by incorporating additional countries, sector-specific emissions, or dynamic models that account for feedback loops between policy variables and investment behavior. Additionally, the long-term role of emerging technologies in decarbonization pathways warrants closer empirical investigation.

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