From Green Policies to Clear Skies: Institutional Pathways of EU Environmental Policy Effectiveness

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Abstract. The role of institutional and economic mechanisms in amplifying the effects of environmental policies is critical for high environmental performance in the European Union. This study examines the complex relationships among environmental taxation (per capita environmental taxes), its mediating mechanisms (Government effectiveness and Regulatory quality), and the amplifying effect of economic capacity (GDP per capita and Gross Fixed Capital Formation) on environmental outcomes (per capita CO_2 emissions). We employ a two-pronged methodological approach: a mediation analysis to identify indirect causal pathways linking environmental taxation to emissions via governance quality, and a Multilayer Perceptron model to capture complex, non-linear interdependencies among fiscal, institutional, and economic variables. The results indicate that environmental taxation reduces CO_2 emissions per capita primarily through indirect effects mediated by government effectiveness and regulatory quality, while economic capacity significantly amplifies these relationships. This methodological shift allows for a mechanism-focused understanding of policy effectiveness, complementing previous configurational insights and providing actionable guidance for EU policymakers.

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1 Introduction

In the context of promoting ecological balance and long-term resilience, achieving high environmental performance in the EU has become a central concern. Despite the proliferation of sustainability-oriented policies, EU member states continue to exhibit heterogeneous environmental outcomes, raising the key question: under which combinations of fiscal, institutional, and economic conditions do countries achieve high environmental performance?

Although substantial literature exists on the conceptualization of environmental performance, there remains a research gap in understanding its determinants across interconnected fiscal, institutional, and economic dimensions. This study aims to address this research gap by constructing an integrated framework based on four pillars and examining the interrelationships among fiscal, institutional, and economic factors that shape environmental outcomes in EU member states between 2012 and 2023. In particular, the research follows the causal processes, decodes complex non-linear correlations, and predictive knowledge concerning the following research objectives:

RQ1: How do environmental taxation policies and institutional quality jointly influence environmental performance?

RQ2: How does economic capacity interact with green fiscal policies and governance to shape environmental outcomes?

RQ3: How do fiscal, institutional, and economic variables collectively and non-linearly contribute to and predict environmental performance?

RQ4: To what extent does institutional quality mediate or moderate the relationship between fiscal policy and environmental outcomes?

The novelty of this research lies in its integrated approach, framed within fundamental environmental economics and governance theories. It demonstrates how environmental taxation indirectly reduces CO_2 emissions through institutional quality, how economic capacity amplifies these effects, and how it captures complex nonlinear interactions using a Multilayer Perceptron model.

The paper is structured as follows: Section 2 reviews the relevant literature, Section 3 presents the methodology and data, Section 4 reports the results, Section 5 discusses the findings, and Section 6 concludes.

2 Literature review

Over the last ten years, both EU policy and academic research have focused on the use of environmental fiscal instruments to achieve a low-carbon economy. Despite this, environmental taxes' share in total tax revenues is on a downward trajectory, falling short of the 2030 climate and fiscal targets, even though environmental taxation remains one of the pillars of the "polluter pays" principle and one of the most essential instruments acknowledged by the European Green Deal [1].

Well-designed, strict environmental regulations, when supported by fiscal instruments, can stimulate innovation by encouraging firms to improve resource efficiency, reduce waste, and adopt cleaner technologies [2]. Also, by associating environmental taxation with an innovation-oriented institutional framework, they reinforce the role of institutional quality as a key mediator in achieving sustainable environmental outcomes [2].

Recent research further shows that the effectiveness of environmental fiscal instruments is influenced by how the policy is conceptualised, implemented, and administered [3]. In fact, instruments alone are insufficient and that, to achieve substantial environmental results, it is generally necessary to use market-based instruments in combination with regulatory measures to eliminate polluting technologies [4]. However, measures of this type are

typically expected to encounter political and institutional opposition, thereby underlining the role of the governance level and administrative capability in ensuring their effectiveness. In the process, the concept of environmental taxation, as a tax on environmental externalities, must be adopted flexibly and in accordance with the institutional and economic conditions in each state, given the overriding role of these variables in the national economy [3].

In parallel, the literature emphasizes the role of economic capacity and investment structures in shaping environmental outcomes. Christou et al. (2025) [5] state that, despite the existence of a common policy framework that meets the EU climate objectives, regional differences in economic capacity strongly influence the setting of investment priorities. The fact that our Multilayer Perceptron model takes into account GDP per capita and Gross Fixed Capital Formation helps address the issue by enabling the assessment of the global predictive role and the enhancing impact of these variables. Changes in one domain, such as economic policy, can produce feedback loops that amplify or counteract outcomes in other domains [6]. This perspective highlights the interdependence between the four pillars of performance in this study, which function as interdependent mechanisms. In fact, fiscal greening instruments require institutional quality for proper implementation and enforcement [3,4,7]; institutional strength shapes the productivity of public and private investment [5,8]; and economic capacity determines a country's ability to absorb, respond to, and benefit from fiscal and regulatory changes [2,5]. Environmental performance thus reflects the cumulative and dynamic impact of these interactions.

Recent empirical studies increasingly examine environmental taxation within broader institutional and economic contexts, showing that fiscal instruments, governance quality, and economic capacity jointly influence environmental outcomes [7,9]. While these studies provide valuable insights, they typically focus on selected interactions or rely on linear econometric approaches. Rather than seeking absolute novelty, our paper aims to contribute to the above-mentioned research by exploring the interaction of fiscal, institutional, and economic dimensions within a single framework, and by exploring the nonlinear interactions of the above factors by using a Multilayer Perceptron model, which allows us to assess more comprehensively the effectiveness of environmental taxation as a result of the interaction of fiscal, institutional, and economic factors.

3 Methodology and data

The study uses a quantitative empirical approach that includes mediation analysis and a Multilayer Perceptron (MLP) model. These methods allow us to uncover not only indirect causal pathways and complex, non-linear relationships, but also to gain predictive insights across fiscal, institutional, economic, and environmental variables over various timeframes. Mediation analysis is crucial for pinpointing indirect transmission mechanisms, whilst the Multilayer Perceptron model captures the intricate, non-linear interdependencies and predictive patterns between variables, aspects that conventional linear models often struggle to address adequately.

To examine how environmental taxation (ET) influences CO_2 emissions per capita (CO2pc) through institutional quality (IQ), we specify the mediation model as follows:

$$IQ_{i,t} = \alpha + \beta_1 \, ET_{i,t} + \epsilon_1$$
$$CO2\_pc_{i,t} = \gamma + \beta_2 \, ET_{i,t} + \beta_3 \, IQ_{i,t} + \epsilon_2 \quad (1)$$

where:

- $ET_{i,t}$= total environmental taxation or carbon-specific taxation for country $i$in year t

- $IQ_{i,t}$= institutional quality measured by Government Effectiveness (GE) and Regulatory Quality (RQ)
- $CO2\_pc_{i,t}$= CO_2 emissions per capita
- β_3= indirect (mediated) effect of ET on CO_2 via institutional quality
- β_2= direct effect of ET on CO_2
- Total effect = $\beta_2 + (\beta_1 \cdot \beta_3)$

This formulation explicitly links the study's indicators and clarifies how institutional quality mediates the impact of environmental taxation on CO_2 emissions.

To capture complex non-linear interactions between fiscal, institutional, and economic factors and predict CO_2 emissions, a feedforward MLP neural network is applied:

$$\widehat{CO2\_pc}_{i,t} = f(W_2 \cdot g(W_1 \cdot X_{i,t} + b_1) + b_2) \quad (2)$$

where:

- $X_{i,t} = [ET_{i,t}, GDP\_pc_{i,t}, GFCF_{i,t}, GE_{i,t}, RQ_{i,t}]$ = *input vector*
- W_1, W_2 = *weight matrices for the hidden and output layers*
- b_1, b_2 = *bias vectors*
- g = *activation function in the hidden layer (e.g., ReLU or sigmoid)*
- f = *activation function at the output layer (linear for regression)*
- $\widehat{CO2\_pc}_{i,t}$ = *predicted CO_2 emissions per capita*

This model enables the identification of nonlinear dependencies, interactions, and thresholds among variables, thereby complementing mediation analysis with predictive insights.

To keep our concepts perfectly aligned with the analytical design, we've carefully categorised all indicators into four key dimensions, following the Four-Pillar Framework: Green Fiscal Instruments, Institutional Quality and Governance, Economic Structure and Investment Capacity, and Environmental Performance. By linking green fiscal instruments, institutional strength, and investment capacity directly to measurable environmental outcomes, our dataset truly reflects the multifaceted nature of sustainability. Using this approach enables a comprehensive assessment of various policy configurations and their contributions to reducing CO_2 emissions. Institutional quality (IQ) is measured using two indicators from the World Bank's Worldwide Governance Indicators (WGI): Government Effectiveness (GE) and Regulatory Quality (RQ) [10]. These indicators reflect the capacity of governments to design and implement sound policies, as well as the ability of regulatory frameworks to support private sector development and policy compliance. Environmental taxation (ET) is measured as total environmental tax revenues per capita, in line with Eurostat definitions [11]. This variable captures each country's fiscal effort to internalize environmental externalities, rather than relying on tax rates or composite indices.

Moreover, the MLP architecture features a supervised regression setup with 5 input nodes (representing TET, GEE, RQ, GFCF, and GDP), a single dense hidden layer, and one output node. The hidden layer employs non-linear activation functions to model complex relationships, whereas the output layer utilizes a linear activation function. The model was trained using an iterative gradient descent algorithm, converging after 6,182 iterations with an error of 19.36. To ensure training stability, input variables were normalized prior to model fitting. Specifically, the training procedure followed a systematic step-by-step process: the network was initialized with 5 inputs, 1 hidden layer (H neurons), and 1 output (CO_2), followed by data preprocessing to clean, normalize, and partition the data into training and validation sets. During each iteration, executed up to 6,182 times or until convergence—the network sampled a batch of observations, performed a forward pass to predict CO_2, calculated the loss, executed a backward pass to compute error gradients, and updated all model weights

using gradient descent. Throughout this process, the error was monitored and logged, ultimately reaching a final value of 19.365.

The resulting database is a standard panel dataset comprising annual figures for all 27 EU Member States between 2012 and 2023. This period marks a very recent and highly relevant decade of fiscal policy development and economic change within the EU, following major economic recalibrations and immediately preceding a period of significant increases in climate policy ambition.

4 Results

In this section, the empirical results of the quantitative analysis are presented, first addressing the mediated causal paths identified by the mediation analysis and, subsequently, the intricate, non-linear relationships and predictions furnished by the Multilayer Perceptron model. The combination of the two approaches offers a holistic perspective on how fiscal, institutional, and economic variables converge to shape environmental performance across the EU Member States.

In addition, the mediation analysis was performed to decompose the mediated relationships through which environmental taxation influences CO_2 emissions per capita, with the mediator being the quality of institutional environments, including the effectiveness and quality of regulatory frameworks. This analysis was made with the specific context of EU Member States between 2012 and 2023. The coefficients on the paths indicated in the mediation model are depicted in Table 1.

Table 1: Mediation Analysis Results for Environmental Taxation, Institutional Quality, and CO_2 Emissions

Path	Label	Est. (coefi)	SE	Z	p-value	95% CI Lower	95% CI Upper	Significant
TT→ GE → CO2pc	Indirect	0.1051	0.0526	1.996	0.034	0.0073	0.2137	*
ET→ GE → CO2pc	Indirect	0.0852	0.0501	1.702	0.066	-0.0023	0.1940	
TaxCO2→ GE→CO2pc	Indirect	0.0177	0.0152	1.171	0.192	-0.0126	0.0469	
TT → RQ → CO2pc	Indirect	0.0328	0.0357	0.928	0.340	-0.0284	0.1103	
ET → RQ → CO2pc	Indirect	0.0351	0.0356	0.996	0.318	-0.0237	0.1144	
TaxCO2→ RQ→ CO2pc	Indirect	-0.0048	0.0163	-0.296	0.712	-0.0377	0.0263	
TT → GE → CO2pc	Direct	0.0898	0.1132	0.794	0.424	-0.1378	0.3060	
ET → GE → CO2pc	Direct	0.0961	0.1036	0.928	0.364	-0.1140	0.2921	
TaxCO2→ GE → CO2pc	Direct	0.0809	0.0259	3.117	0.000	0.0291	0.1309	***
TT → RQ → CO2pc	Direct	0.1977	0.1153	1.714	0.102	-0.0255	0.4267	
ET → RQ → CO2pc	Direct	0.1886	0.1026	1.837	0.056	-0.0087	0.3937	

Path	Label	Est. (coefi)	SE	Z	p-value	95% CI Lower	95% CI Upper	Significant
TaxCO2→ RQ→ CO2pc	Direct	0.1112	0.0277	4.002	0.000	0.0592	0.1681	***
TT → GE → CO2pc	Total Effect	0.1950	0.1248	1.562	0.118	-0.0497	0.4397	
ET → GE → CO2pc	Total Effect	0.1814	0.1151	1.576	0.115	-0.0441	0.4070	
TaxCO2→ GE → CO2pc	Total Effect	0.0987	0.0300	3.282	0.001	0.0397	0.1576	**
TT → RQ → CO2pc	Total Effect	0.2306	0.1207	1.911	0.056	-0.0059	0.4672	
ET → RQ → CO2pc	Total Effect	0.2237	0.1085	2.061	0.039	0.0109	0.4365	*
TaxCO2→ RQ→ CO2pc	Total Effect	0.1064	0.03224	3.3	0.0009	0.0432	0.1696	***

Our results suggest that the mediation test indicates that the role of institutional quality varies across tax types and institutional quality measures. The combination of the effects of environmental taxation on institutional quality (path "a") and institutional quality on either CO_2 emissions per capita (path "b") is described in the indirect effect. Although the total effect of environmental taxation on CO_2 emissions (path "c") for the relationship "TT → GE → CO2pc" was not statistically significant (Est. = 0.195015, p = 0.118), the direct effect (path "c") for the same relationship became statistically non-significant (Est. = 0.089895, p = 0.424) after the inclusion of institutional quality (Table 1).

Most importantly, however, the indirect effect (a, b) of total environmental taxation (TT) on CO_2 emissions, which occurred via government effectiveness, turned out to be positive and statistically significant at Est. = 0.105121 and p = 0.034, respectively. The implication is that the government's effectiveness is essential to the effectiveness of total environmental taxation in reducing CO_2 emissions. These results confirm the critical role of governance structures in achieving effective environmental fiscal policy. This pattern of results indicates a case of full (or dominant) mediation. Specifically, once Government Effectiveness is included in the model, the direct effect of total environmental taxation on per capita CO_2 emissions becomes statistically insignificant, whereas the indirect effect remains significant. This suggests that the impact of total environmental taxation on emissions reduction operates primarily through institutional effectiveness rather than through a direct fiscal channel. Importantly, this finding does not imply that environmental taxation is ineffective per se, but rather that its effectiveness is strongly conditioned by the quality of governance structures responsible for implementation and enforcement. The literature reiterates that the quality of institutions plays an instrumental role in determining the effectiveness of environmental policies. For the individual coefficients of path 'a (Environmental Taxation → Institutional Quality) and path 'b' (Institutional Quality → CO_2 Emissions controlling for Environmental Taxation), the table below provides only the aggregated indirect, direct, and total effects. To derive these individual coefficients, regression results from the underlying mediation model would be needed.

Furthermore, leveraging the knowledge acquired from the mediation analysis, it is necessary to move forward in our analysis and introduce the other neural network model – the Multilayer Perceptron, to grasp the complex relations and gain predictive knowledge

about the impact of the Green Fiscal Instruments, the Institutional Factors, and the Economic Capacity on the Environmental Performance (CO2 emissions per capita).
This enabled us to explore complicated interdependencies that may not be fully reconstructed by linear models. The performance measure of the trained MLP neural network is represented in Fig.1.

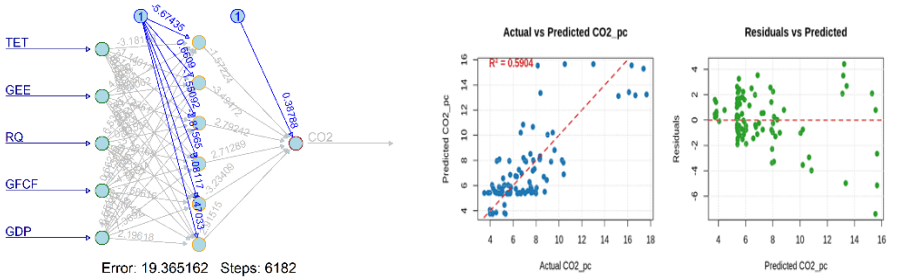

Fig. 1. Structure of the Multilayer Perceptron model and output predictions

The Multilayer Perceptron model provides a visual and analytical understanding of the complex relationships between input variables—including env_taxes_total, gdp_pc, gfcf, GE, and RQ—and CO via a hidden layer. In the present study, the MLP model achieves a moderate explanatory power, with an R^2 of approximately 0.5904, indicating a reasonable ability to capture overall trends in CO_2 emissions across EU Member States, but also highlighting limitations in explaining extreme values. References to high predictive accuracy in the literature reflect performance under different datasets or model specifications and should not be interpreted as indicative of the global fit of the model estimated in this analysis. Through sensitivity analysis and variable importance techniques, the MLP identifies key predictors, such as economic indicators and institutional factors, and reveals complex nonlinear interactions, thresholds, and synergistic effects, all of which are essential for formulating effective climate policies.

Meanwhile, the analysis of the Multilayer Perceptron model's predictions indicates a moderate explanatory capacity, with a coefficient of determination (R-square) of approximately 0.5904. This suggests that the model is efficient in capturing general trends but exhibits a substantial error for specific observations. A notable aspect is the tendency to underestimate high CO_2 values, as reflected in large negative residuals for high predictions. At the same time, there isn't a clear non-linear relationship between residuals and predictions, greater variation in errors is observed at the extremes of the distribution. In the average range of CO_2 (~5–9), predictions are relatively stable, with moderate residuals. Additional calculations on the Actual Predicted Error list confirm this moderate performance, with typical errors between ~0.5 and ~2.5, but also with a few serious outliers that can influence global metrics. The general bias (mean of errors) is slightly negative, indicating a slight average underestimation, although the presence of outliers dominates the mean squared error.

5 Discussion

A more complex analysis of the impact of environmental taxes on per capita emissions, using mediation analysis and MLP networks, provides a holistic perspective on the aforementioned interrelationships. Using mediation analysis, the complex relationships between environmental taxes and institutional quality have been examined. The relationship to be analyzed is that total environmental taxes indirectly affect emissions reductions through the government's effectiveness. In contrast, carbon-specific taxes demonstrated a strong, direct influence on emissions levels, operating generally independently of institutional factors.

In contrast, carbon-specific taxes demonstrated a strong, direct influence on emissions levels, operating generally independently of institutional factors. This finding indicates that, while strong institutional quality generally enhances policy effectiveness, certain well-designed fiscal instruments, such as carbon taxes, may generate measurable environmental outcomes even in contexts with weaker governance. This has important policy implications: countries with lower institutional capacity can still implement carbon-specific taxes as an effective climate policy, although complementary efforts to strengthen governance can further amplify the impact of these measures. This nuance reconciles our empirical observation with the theoretical framework, emphasizing the enabling role of institutions in translating fiscal policy into sustainable outcomes.

Although Regulatory Quality's mediating role in those indirect relationships is less relevant, it remained highly correlated with the total influence of energy taxes. From a theoretical perspective, the identification of Government Effectiveness as a fully mediating variable does not imply that institutional quality replaces fiscal instruments. Instead, institutional quality functions as an enabling transmission mechanism that allows environmental taxation to be translated into effective enforcement, compliance, and behavioral change. In the absence of sufficient administrative capacity, broad-based environmental taxes may fail to generate a direct emissions-reduction effect, whereas stronger institutional environments allow these fiscal instruments to operate as intended.

The Multilayer Perceptron served as an auxiliary tool for analysis, as it could identify nonlinear relationships that other analyses failed to reveal. The sophisticated model, with input variables such as TT, GDP, GFCF, GE, and RQ, is reliable for predicting environmental efficiency, particularly the impact of per-capita emissions. The MLP model has long been widely praised for the accuracy of its predictions and its ability to identify key variables and nonlinear patterns in the analysed data. Its capacity to distinguish complex patterns/or thresholds, and to capture interactions among variables, is, in any case, a key component of the comprehensive analysis of the common impact of environmental fiscal tools, institutional quality, and economic capacity.

Nevertheless, the MLP model developed in this study exhibits only moderate explanatory power, with an R^2 of approximately 0.5904. This outcome can be explained by the asymmetric distribution of CO_2 emissions across EU Member States, in which high-emission observations are relatively infrequent and exert disproportionate influence on prediction errors. As a result, the model tends to prioritize accuracy around average emission levels, leading to a systematic underestimation of high-emission values and increased error variability in the upper tail of the distribution.

These limitations have important implications for interpretation and policy relevance. While the MLP model is well suited for identifying general nonlinear patterns, interaction effects, and average trends, its predictive reliability is reduced in high-emission contexts, where structural, sector-specific, or country-specific factors may dominate. Consequently, the MLP results should be interpreted as complementary to the mediation analysis, rather than as a standalone tool for policy guidance targeting extreme emission scenarios.

While the MLP model provides valuable insights into nonlinear relationships and average emission dynamics, its tendency to underestimate high CO_2 emission levels limits its applicability for policy design focused exclusively on high-emission contexts, underscoring the need for complementary modeling approaches in future research.

6 Conclusion

This research aimed to examine the effects of environmental taxation on CO_2 emissions by employing a complementary analytical approach that combines mediation analysis with a multilayer perceptron model. The mediation analysis revealed that the impact of total

environmental taxes on reduced CO_2 emissions was indirectly mediated by institutional quality, with governmental effectiveness as the mediating variable. However, carbon-specific taxes demonstrated a strong, direct influence on CO_2 emissions, operating generally independently of institutional factors. This suggests that while institutional quality is generally essential for policy effectiveness, certain well-designed fiscal instruments, such as carbon taxes, can produce measurable outcomes even in countries with weaker governance. This finding has important policy implications, indicating that carbon taxation can be an effective tool for climate mitigation across diverse institutional contexts, though complementary governance strengthening can further enhance effectiveness. Overall, the findings indicate that while carbon-specific taxes exert a strong and direct influence on CO_2 emissions, the effectiveness of total environmental taxation is predominantly mediated by institutional quality, highlighting the central role of governance capacity in EU environmental policy effectiveness.

The application of the MLP model has reaffirmed that this approach can recognize potentially complex nonlinear interdependencies, thereby providing a comprehensive view of the interactive relationships among economic, institutional, and fiscal factors influencing environmental performance. While the MLP model contributed to understanding nonlinear dynamics and, in general, demonstrated robust predictive performance, with an R-squared of approximately 0.5904 for the case analysed, it is not without limitations. Limitations include a tendency to underestimate high CO_2 emissions and greater variability in errors at both extremes of the distribution. This underscores that, although the model is overall good at capturing general trends, its accuracy can be further refined for extreme, radical emission scenarios. Future research should focus on refining the MLP architecture, selecting optimal features, and using expanded data to improve predictive power and provide more detailed tools for climate policy formulation, particularly in the context of ambitious emission-reduction targets.

These findings suggest that EU policymakers should implement fiscal measures, such as carbon taxes, alongside capacity-building in governance to maximize both direct and institution-mediated environmental outcomes, while considering context-specific measures in high-emission settings.

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Appendix

Table A1: Driscoll-Kraay standard errors

	estimate	Std_error	z-value	P_palue
CO2	-1834.324	500.554	-3.664	0.0002***
GEE	-3193.376	2099.736	-1.520	0.1293
RQ	-267.230	3249.487	-0.082	0.9345
GFCF	298.046	92.10079	3.236	0.0013**
TET	0.05569	0.062039	0.897	0.3700

Table A2: Pesaran CD test

Test	Statistic	Prob
Pesaran CD	18.67298	0.0000