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Green Leverage: How CO_2 Emissions Shape Capital Structures in EU Corporations

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ABSTRACT

This paper examines the interaction between firm leverage and carbon emissions in the European Union, with an emphasis on how corporate environmental performance affects the capital structure of firms. Based on an unbalanced panel of 4,183 firm-year observations from 819 EU listed firms for the period 2010-2024, we use dynamic panel estimation methods (System-GMM) to examine the impact of CO_2-equivalent emissions on leverage. The analysis is conditioned on firm-specific financial attributes, profitability, size of firm, tangibility, liquidity, capitalization, and governance factors, including board gender diversity and board size. The empirical findings show a statistically significant negative correlation between firm leverage and carbon emissions, implying that firms with high emissions have the propensity to decrease their debt dependence. This correlation is particularly notable in the case of larger firms, as they are more exposed to regulatory treatment and reputational threats. Financial attributes like increased profitability and equity capitalization also go with lower leverage, while tangibility and liquidity enhance debt capacity. Robustness tests validate consistency of results across firm size groups. The research concludes that carbon emissions are becoming an important determinant of financial decision making, sustaining the importance of environmental performance integration into risk measurement and credit allocation models. These results have important policy implications, calling for more robust carbon disclosure requirements and extending sustainable finance mechanisms. Companies are stimulated to adapt their capital structure for climate goals to promote long-term financial resilience and regulatory compliance in an ESG-sensitive market regime.

Keywords: Carbon Emissions, Firm Leverage, Sustainable Finance, Corporate Governance, Profitability
JEL Classifications: G32, Q56, M14, G34

1. INTRODUCTION

Climate change has emerged as one of the world's most urgent issues, with deep reaching implications for environmental, social, as well as economic spheres. Of the many causes of climate change, carbon emissions most notably greenhouse gases (GHGs) have been identified as the causative agents of global warming and ecological imbalance. With the need to reduce these emissions growing ever more urgently, the nexus between environmental sustainability and financial stability has assumed greater salience. Characteristic of contemporary times, companies' carbon footprints are no longer purely environmental issues but now also important drivers of their capital accessibility, borrowing costs, and financial well-being. Even in the face of high levels of acknowledgment regarding the necessity of lowering carbon emissions, a bedrock issue has not been fully answered: How do absolute values of a company's carbon emissions affect its leverage choices within the European Union (EU)? Specifically, to what degree do strategic low-carbon technology investments, carbon offset projects, and effective carbon assurance programs reduce the negative financial effects that come with high emissions? Understanding these connections is crucial to investors, policymakers, and firm managers trying to make sense of climate related financial risks.

The last 10 years have seen tremendous growth in comprehending the cost of climate change for finance. Regulatory guidelines like the EU Emissions Trading System (EU ETS), the EU Taxonomy for green activities, and more stringent disclosure obligations under the Non-Financial Reporting Directive (NFRD) have reshaped the face of corporate environmental responsibility. These policy measures have increased the risks for companies operating in carbon intensive industries, forcing them to factor in climate risk in their strategic and financial decision-making. Studies have found that climate transition risks like tighter regulations, carbon charges, and reputational threats are being more and more factored into companies' borrowing costs and credit spreads (Han et al., 2023; Bolton and Kacperczyk, 2023). For example, polluting firms in the EU experience higher debt spreads and tighter loan covenants, as markets view their regulatory and environmental exposures as a risk. In addition, the implementation of climate risks in financial markets created an increase in credit default swap (CDS) spreads, which are used as proxies for implied default risk associated with climate transition exposure (Zhang et al., 2023).

Technological advancements have become key enablers for companies seeking to decrease their carbon burdens as well as strengthen financial stability. Low carbon technologies like Carbon Capture and Storage (CCS), renewable energy uptake, and energy efficiency improvements enable reduction of emissions at lower costs compared to traditional regulatory compliance. Several companies are also increasingly making investments in voluntary carbon offsetting programs whose aim is to offset remaining emissions, enabling companies to be carbon neutral and satisfy stakeholders' demands for less (André and Valenciano-Salazar, 2022).

(He et al., 2022) has focused on the direction of CO_2 emissions, especially with regard to innovation and environmental practices. Research indicates that innovation, R&D expenditure, and technological advancements are keys to lowering firms' CO_2 emissions. The validity of such offsetting measures is oftentimes substantiated by third party verification and assurance, and this can affect investor confidence and minimize perceived environmental risks. Also, strategic investments in low carbon technologies are not only eco-friendly but also economic strategy. Companies that make good use of such technologies have the potential to reduce future compliance expenses, minimize carbon tax exposure, and improve their ability to adapt to changing regulatory landscapes. For instance, CCS investment can yield long-term gains by sequestering and storing emissions that would otherwise earn penalties, hence having a positive effect on the leverage capacity of a firm by reducing perceived finance risks related to carbon liabilities (Singh et al., 2022).

Aside from operational and technological strategies, the function of credible assurance providers and governance mechanisms also plays a significant part in alleviating carbon emission-related financial risk. Companies that hire credible third-party accountants or sustainability certifiers to authenticate their emissions data and offset claims benefit from a lower cost of equity as well as better market perceptions (Alkebsee et al., 2025). This trustworthiness minimizes information asymmetries and maximizes stakeholder trust, which can be reflected in more beneficial terms of financing.

In spite of all these advancements, there still exists an immense empirical research gap to directly study how absolute carbon emissions affect firm leverage, especially in the EU setting where regulatory and market forces are uniquely sophisticated. The majority of current studies concentrate on ESG scores, self-disclosures, or reputational environmental performance, which do not explicitly reflect firms' actual environmental footprints (Sun, 2024; Arvidsson and Dumay, 2022). As a result, the link between measurable emissions data like total CO_2-equivalent emissions (CO_2e) and capital structure is under investigated.

In addition, although the literature acknowledges the role of technological innovations, offsetting, and assurance in climate risk management, their moderating roles in the nexus between emissions leverage are not clear. It is not certain whether low carbon technology investment and the reliability of emissions reporting have the ability to counteract the detrimental effect of high emissions on leverage levels. This remains specifically salient in the EU, with tight policy requirements and high stakeholder demands for transparency and accountability. Filling this gap is important for a variety of reasons. First, for policymakers, knowing how actual emissions by firm's impact financial stability can better guide more effective regulation and incentives to encourage sustainability (Anastasiou et al., 2024). Second, for investors and financial institutions, knowledge of the mitigating impacts of low carbon investments and reliable assurance mechanisms can result in more effective risk assessment and superior capital allocation. Third, for companies themselves, understanding the relationship between emissions and leverage can inform strategic choices whether to invest in emissions-reducing technologies, engage in offsetting efforts, or increase transparency through third-party verification.

For the overall EU setting of its ambitious climate ambition to achieve climate neutrality by 2050 knowledge of the financial dynamics of emissions and leverage is vital. The regulatory EU landscape, defined by the EU ETS, taxonomy classification, and disclosure directives, drives the behavior and financial policies of firms. Empirical findings specific to this context, therefore, can offer important recommendations for corporate managers, regulators, and investors who have to guide the way towards a low-carbon economy.

Specifically, this study addresses the following research questions: (1) How do firm-level CO_2-equivalent emissions influence leverage ratios among EU listed firms? (2) To what extent do firm specific financial characteristics such as profitability, size, and tangibility condition this relationship? (3) Does the effect of emissions on leverage differ between large and small firms, reflecting asymmetries in regulatory exposure and capital market sensitivity? (4) What role do governance related variables, including board gender diversity and board size, play in shaping leverage outcomes in high emission firms? (5) What actionable insights can be drawn for corporate finance strategies and sustainable financial regulation in the European Union?

By delivering empirical evidence across firm sizes, industries, and governance profiles, this research deepens the understanding of the financial implications of carbon exposure and supports the strategic integration of environmental performance into corporate capital structure decisions. In doing so, the study advances the discourse on sustainable finance by clarifying how carbon risk translates into leverage behavior, thereby reinforcing the relevance of emissions accountability in shaping financial resilience and ESG-aligned policy outcomes.

The rest of this paper is structured as follows: Section 2 discusses the applicable theoretical foundations and earlier empirical research. Section 3 outlines the data, the variables, and the empirics used to examine the hypothesis. Section 4 reports empirical findings, along with robustness checks. Section 5 discusses policy implications, limitations, and scope for further research.

2. LITERATURE REVIEW

2.1. Financial Risk and Carbon Emissions

The link between carbon emissions and financial risk is increasingly explored using signaling theory and stakeholder theory. Under signaling theory, companies can employ capital structure choices and sustainability disclosures to signal environmental responsibility in the hope of impacting the perception of investors and lowering financing costs. (Hágen and Ahmed, 2024) establish that the best capital structure in GCC companies reduces the adverse impact of carbon emissions on firm value, with leverage as a signaling device. Likewise, (Zhou et al., 2025) show that carbon management by supplier's lowers idiosyncratic risk through information asymmetry. Stakeholder theory focuses on how companies react to external expectations of environmental performance. (Nguyen and Phan, 2020a) demonstrate that leverage and ISO certification affect carbon disclosure as a reflection of strategic attempts to align with stakeholder issues. Stakeholder dynamics are also supported in "ESG and Leverage Adjustment: Based on Stakeholder Theory and Signaling Theory" (2024), which demonstrates how companies adapt financial strategies during times of economic instability in order to weigh transparency against stakeholder involvement.

High carbon emissions are also linked with high idiosyncratic risk and capital expenses, as evidenced by (Arian and Sands, 2024). Companies that are better at managing carbon risk make disclosures of better quality, which enhance legitimacy but not necessarily decrease cost of equity. (Liu and Zhang, 2022) contend that carbon intensive companies utilize strategic disclosures to counteract legitimacy risks, whereas (Domenichelli, 2023; Zhou et al., 2025) illustrates that such companies tend to have lower financial leverage owing to greater financial distress costs. (Moussa and Elmarzouky, 2024) highlight that sustainability reporting enhances transparency and crash risk reduction, complementing the signaling function of high quality disclosures. As (Moussa and Elmarzouky, 2024) argue, these practices ultimately create greater market efficiency through minimizing information asymmetry in financial decision making.

2.2. Proxying Risk through Emissions and Their Effect on Creditworthiness

Carbon emissions are universally accepted to be a proxy for reputational, operational, and regulatory risk, particularly in heavily polluting industries. (Guastella et al., 2023) establish that companies with high Scope 3 emissions incur reputational costs that hinder revenue growth under ambitious climate policies. (Zoltáni, 2013) also adds that carbon can serve as a financial instrument to regulate reputational and compliance related risks. Empirical research conducted by (Ventouri et al., 2023) and (Ventouri et al., 2023) supports the fact that increased corporate pollution rates correlate with lower reputational ratings, especially in climate vulnerable areas. (Szendrey and Dombi, 2024) highlight the importance of considering indirect emissions within risk evaluations, as they tend to account for a significant percentage of overall emissions and affect both compliance results and market image.

In capital markets, emissions performance also meaningfully influences a company's borrowing cost. The transparency in disclosure of emissions, particularly Scope 3 has been linked with reduced borrowing costs, with (Panjwani et al., 2022) noting a disclosure premium of around 20 basis points. Conversely, (Maaloul, 2018) records that increased emissions raise the cost of debt by 11-15% per tonne for Canadian companies. Equally, (Kozak, 2021) discovers that EU companies with lower carbon intensity experience lower funding costs, echoing increasing lender awareness of climate risk.

Quality of disclosure also matters. Companies that disclose carbon information on a voluntary basis have lower loan spreads, particularly with high asymmetry of information (Kleimeier and Viehs, 2018; Haque, 2017) affirm that good quality GHG disclosure increases perceived environmental integrity, leading to better lending conditions. (Hu and Liang, 2024) further stipulates that such impacts are greater among private companies and in more unregulated environments, pointing out the way emissions management increasingly shapes financial access and pricing.

2.3. Carbon Emissions and Firm Leverage

Meanwhile, one of the interesting studies in the literature examines the links between carbon emissions and firm capital structure. High emission firms are said to keep lower leverage because the higher the leverage, the more financial distress risk they are facing due to climate regulations. For instance, studies concerning the Kyoto Protocol in Australia and China's carbon pilot policy highlight the decrease in leverage of polluting sectors linked with increased capital constraints (Nguyen and Phan, 2020b; Han et al., 2023). These findings supported the trade-off theory, stating that distress and tax costs from being carbon-intensive have started to outweigh the benefits of tax shields and hence deter such firms from excessive debt usage (Domenichelli, 2023; Demirgüç-Kunt et al., 1999). In addition, due to carbon emissions also increasing idiosyncratic risk and financing costs, these firms might be further discouraged from resorting to debt (Arian and Sands, 2024).

Increasing leverage also offers a firm's perspective in determining how to disclose carbon. The Indonesian context shows that leverage explains more than 26% of carbon emission disclosure variance, (García-Gómez et al., 2021) implying that highly leveraged firms tend to disclose environmental information, possibly for reputational reasons or for compliance (Ratmono et al., 2021; Yulianti and Waworuntu, 2024). These particularly relate to the case of Indonesian manufacturing, where the mechanism has been proven, although firms' size and environmental performance appear to have limited explanatory power (Putri and Trisnawati, 2023). On a European stage, carbon emissions negatively affect firm value; this is especially true for the highly polluting firms, wherein emissions detract from the informativeness of earnings (Perdichizzi et al., 2024). Similar set-ups happen also across African markets, in instances where GHG intensity harms financial results such as ROA and ROE, mostly in heavily polluting industries (Le and Nguyen-Phung, 2024). These routes evince the twofold role played by emissions in firm financial leverage strategy and valuation arenas.

The EU ETS further sheds light here, as carbon pricing impacts on the capital accessibility and hence investment. By the combination of flexible trading of allowances and a Market Stability Reserve, the EU ETS has secured emission reductions in the regulated sectors (Vollebergh and Brink, 2020; Richstein et al., 2015). Prior studies indicate that firms with higher carbon emissions often face greater financial constraints due to regulatory pressure, reputational risks, and increased borrowing costs. These risks reduce their capacity or willingness to use debt financing, particularly in emission-intensive sectors. Consistent patterns across various jurisdictions support a negative link between emissions and leverage. Based on this evidence, the study proposes the following hypothesis:

Hypothesis (H1): CO_2-equivalent emissions have a negative impact on firm leverage.

2.4. Firm Specific Financial Controls and Leverage

2.4.1. Profitability, liquidity, and tangibility

Profitability and Leverage relations are subtle and differ from one industry to another. In the cement industry, leverage negatively correlates with return on assets and net profit margins (Heath and Sertsios, 2022), whereas the return on equity seems not to be influenced at all (Daruwala, 2023). On the contrary, the oil and gas firms show mixed results; some affirm a positive correlation between leverage and EPS, while others assert the opposite, thereby suggesting that the impact of leverage on profitability cannot be generalized (Yusri and Syafiq, 2023) Further insights by Baker (1973) also assert that lower leverage firms experience higher levels of profitability, refuting the assertion that debt magnifies returns differs in different industries.

This adjustment behavior concerning leverage depends on the size of firms as well. Larger firms tend to make gradual leverage adjustments in relation to changes in market conditions, while smaller ones make swifter adjustments in relation to changes in market power and profitability pressures (Alter and Elekdag, 2020). These dynamics underscore the importance of considering industry context, profitability structure, and liquidity in capital structure analysis.

2.4.2. Firm size and capitalization

Firm size and capitalization constitute the very determinants of debt capacity. A study carried out by (D'Amato, 2020) states that the bigger firms minimize short-term debt in favor of long-term sources of finance, while the opposite is true for smaller firms that rely mostly on short-term borrowing given their limited access to capital markets. Another study by Gonzalez (2014) finds that size is an important factor affecting the maturity structure of debt, given that larger firms differ in their management of agency costs and in their signaling when compared to their smaller counterparts.

The pecking order theory suggests that firms with more unused debt capacity generally finance more of their financial deficits through borrowing, up to about 50%, while the low capacity ones only borrow up to 25% (Fosberg, 2008). Nevertheless, going beyond the optimal levels of debt would be bad. (Karas and Režňáková 2023) talk about surpassing the sustainable levels of debt with adverse consequences, whereas (Chung et al., 2013) find that optimal capital structure decisions defined by firm size and capitalization are essential to sustaining firm value and reducing exposure to financial risks.

2.5. Corporate Governance, Sustainability Incentives, and Leverage

Corporate governance mechanisms, particularly concerning boards' structural formations and diversities, lead firms in their final loci over capital structure and sustainability orientation. Firms that have solid governance are known to generally set very low leverage levels, whereas weak governance induces behavior that forces reliance on debt as a means to exercise control (Chang et al., 2014; Jiraporn et al., 2012). Board diversity, both demographic and structural, is positively correlated with eco-innovation and sustainability practices (Zaman et al., 2024). Linking top executives' pay to ESG objectives is therefore a responsible governance practice that moves toward the creation of long-term value in preference to short-term gains (Nasta et al., 2024). Gender, to a certain extent, brings efficiency to boards and strengthens governance signals into capital markets (Amin et al., 2022). Well-diverse boards make better decisions regarding capital structures and increase lenders' confidence (Amin et al., 2022). An effective governance system marked by diversity and sustainability incentives makes the firm more attractive to its investors, hence contributes to resilience in the long run (Salvioni and Gennari, 2014). The environmental-financial performance relationship is significantly influenced by the nature of the institutional quality and regulatory frameworks existing for operations by firms. High-level quality institutions usually enhance ESG outcomes, which in turn have a positive correlation with financial returns, especially in politically stabilised and well-regulated environments (Provaty et al., 2024; Boccaletti and Gucciardi, 2025). Developed countries thus promote socially responsible investing, while emerging markets tend to rank lower in emphasis on socially responsible investments due to institutional deficiencies that weaken the economics of ESG on financial returns (Garcia and Orsato, 2020).

Negative externalities can be avoided under an underdeveloped regulatory systems. (Latif et al., 2023) acknowledge the ability of regulation to reduce the environment cost of financial inclusion, emphasizing governance as a bridge between development and sustainability. Governance quality is asserted by Khan et al. (2024), Wyns (2015), and Xie et al. (2019) to be what can enable corporate environmental strategies with sufficient leverage to achieve concrete financial returns.

3. RESEARCH DESIGN

3.1. Sample Selection and Data Collection

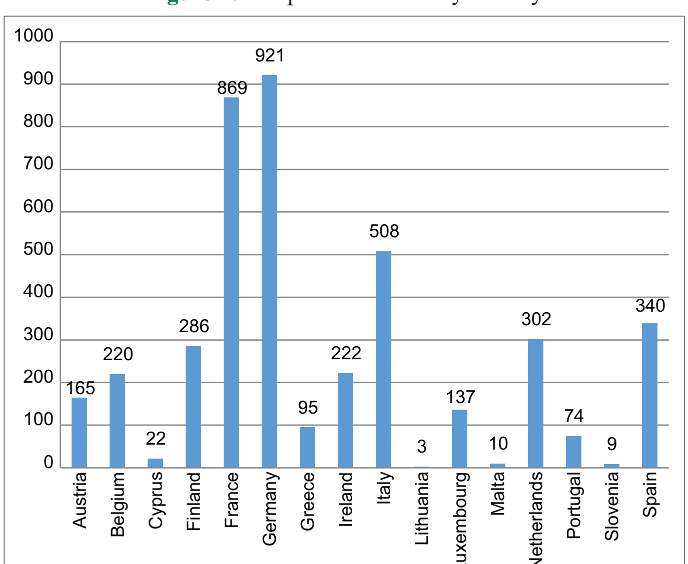
The study investigates the link between CO_2 Equivalent Emissions Total related to Leverage. To enhance analytical rigor, observations with incomplete financial data were excluded, yielding a final unbalanced panel of 4,183 firm-year observations from 819 EU-based companies spanning 2010-2024. Data analysis employed STATA software, using a dataset sourced from LSEG data stream, a reputable provider of economic and financial information. Table 1 and Figure 1 illustrate the sample selection methodology and offer detailed insights into the country-specific distributional characteristics of the dataset.

Table 1: Sample distribution by country

Country	Total observations
Austria	165
Belgium	220
Cyprus	22
Finland	286
France	869
Germany	921
Greece	95
Ireland	222
Italy	508
Lithuania	3
Luxembourg	137
Malta	10
Netherlands	302
Portugal	74
Slovenia	9
Spain	340
Total	**4183**

This table provides the distributional properties of the full sample by country. Observations are the total of the firm-years observations

Figure 1: Sample distribution by country



3.2. Variables

The empirical inquiry is based upon the variables, which can be arranged under dependent variables, independent variables, and control variables. The whole set of data is sourced from the LSEG (Datastream), known as the ultimate database for environmental, financial, and governance information at the firm level. These variables try to capture important facets of the financial structure, ecological exposures, and internal governance mechanisms, which are relevant to the capital structure decisions of European Union based companies.

3.2.1. Dependent variable

3.2.1.1. Leverage (lev)

In a nutshell, leverage (Lev), defined as the debt-to-total assets ratio, and defines the extent to which a company relies on external financing and its associated financial risk. It holds an important role in sustaining a company and in the disclosure of carbon emissions, accounting for 26.47% according to Hurdle (1974). A higher leverage allows a firm to invest on clean technology and operational efficiency needed to reduce emissions, especially if it comes from highly polluting industries such as oil and gas (Dong et al., 2020). Leverage companies will also begin CSR practices that improve the perception of the corporate world and trust with stakeholders, such as improving energy efficiency and transitioning into renewable energy (Balukja, 2024). Along with this is sustainable operations management among others in the external supply chain in demonstrating how leverage can be used for cooperative emission reductions (Mubarik et al., 2025). So, leverage not only represents the capital structure alternatives but also sustains performance on sustainability and accountability in solving environmental issues.

3.2.2. Independent variable

3.2.2.1. CO_2 equivalent emissions total (CO_2)

The chief independent variable in this analysis is total CO_2 emissions, covering all direct and indirect greenhouse gas emissions into the atmosphere. The emissions variable is measured in metric tonnes and is taken under natural logarithmic transformation to reduce skewness and validate its normality across firms of different scale. (Lee et al., 2024; D'oultremont & C. 2010) CO_2 emissions serve as an indicator for environmental risk and regulatory exposure, thus giving a notion of how environmentally intensive operations may impinge upon leverage decisions. (Liu and Zhang, 2022) Data collection was done from regions in China for the period 2003-2017 and found that generally uncertainty harms carbon emissions except in the central and western regions of China.

3.2.3. Control variables

The study will include these control variables in order to account for firm-specific variables that may affect leverage independent of emissions such as financial fundamentals and governance characteristics. Return on Assets (ROA = Net Income/Total Assets), which serves as a proxy for operational efficiency and profitability, is included as a control variable. According to pecking order theory, more profitable firms tend to use internal financing and thus should show a negative relation with leverage (Kamila, 2024) found that profitability hit leverage in Indonesian manufacturing firms. There exists a negative and statistically significant association between CO_2 emissions and profitability, corporate liquidity, and institutional shareholdings (Benlemlih and Yavaş, 2024; Bolton and Kacperczyk, 2021; Hossain et al., 2023; Safiullah et al., 2022).

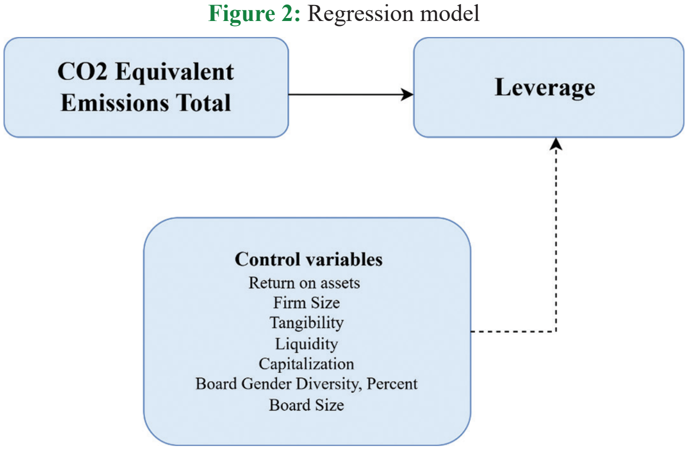
Firm size (FS), measured as the natural logarithm of total assets, reflects a firm's scale and borrowing capacity; larger firms are generally more diversified and enjoy better access to credit, potentially resulting in higher leverage ratios (Brighi and Venturelli, 2014). Firm size is included in the regression, as larger companies typically emit more CO_2 emissions due to the scale of operations (Provaty et al., 2024). Tangibility (Tang), defined as the ratio of tangible assets to total assets, indicates collateral availability, which is often associated with increased debt capacity due to the asset backing of loans (Boasiako et al., 2022). Liquidity (Liq), measured as the difference between current assets and current liabilities divided by total assets, captures short-term solvency. Higher liquidity typically reduces the need for external debt financing (Grobéty, 2018). Capitalization (Cap), computed as equity capital divided by total assets, reflects the firm's internal financing structure; firms with higher capitalization may maintain lower leverage as they rely more on equity (Graham et al., 2015). Governance related controls include Board Gender Diversity (BGD), measured by the percentage of female directors on the board. Board diversity has been associated with improved decision-making, risk oversight, and long-term strategic orientation, all of which can influence capital structure choices (Yakubu and Oumarou, 2023). Lastly, Board Size (BS), representing the total number of board members, reflects governance scale and capacity. While larger boards may enhance oversight, they can also lead to inefficiencies or conflicting strategic preferences, potentially affecting a firm's risk tolerance and financial leverage (Nakano and Nguyen, 2012).

3.3. Regression Model

A regression analysis examined the relationship among CO_2 Equivalent Emissions Total and Leverage. Figure 2 visually represents these hypothesized relationships, with Table 2 outlining variable definitions. Year and industry fixed effects were included to account for temporal differences in the data.

$$Lev_{i,t} = \beta_{10} + \beta_{11}\, Lev_{i,t-1} + \beta_{12}\, CO2_{i,t} + \beta_{13}\, ROA_{i,t} + \beta_{14}\, FS_{i,t} + \beta_{15}\, Tang_{i,t} + \beta_{16}\, Liq_{i,t} + \beta_{17}\, Cap_{i,t} + \beta_{18}\, BGD_{i,t} + \beta_{19}\, BS_{i,t} + \text{Fixed effects}_{i,t} + \varepsilon_{1\,i,t} \quad \text{Model (1)}$$

Figure 2: Regression model



4. RESULTS AND DISCUSSION

4.1. Descriptive Statistics

The descriptive statistics presented in Table 3 summarize the characteristics of 4,183 firm-year observations from EU-listed companies over the 2010-2024 period. The average firm leverage ratio is 0.30, indicating moderate reliance on debt, with variation evident from a standard deviation of 0.18. Carbon emissions (CO_2), reported in logarithmic form, show a mean of 11.35 and a wide dispersion, suggesting substantial differences in environmental impact across firms. Among control variables, profitability (ROA) averages 3%, while firm size (log of total assets) centres around 9.64. Tangible assets comprise approximately 60% of total assets on average, and liquidity is modest, though some firms exhibit signs of short-term distress. The average capitalization level is 0.37, with a few firms showing negative equity. In terms of governance, board gender diversity averages 33%, with some boards entirely male and others having up to 75% female representation. Board size ranges broadly, with an average of 11 members. Overall, the data reflect meaningful variation in financial structure, emissions intensity, and governance characteristics providing a strong basis for the subsequent multivariate analysis.

4.2. Kernel Distribution Technique

Figure 3 presents the kernel density plots for the key variables included in the regression analysis. The kernel distribution technique provides a smooth estimation of the probability density function, allowing for the assessment of the normality and shape of variable distributions.

The plots reveal that most variables including leverage (Lev) and CO_2 emissions (log-transformed) approximate a bell-shaped curve, suggesting near-normal distributions suitable for linear regression analysis. Notably, ROA, liquidity, and capitalization exhibit mild skewness, likely due to the presence of firms with extreme financial conditions (Kinyua and Fredrick, 2022) (e.g., negative earnings or equity). Board gender diversity (BGD) shows moderate right skewness, reflecting the presence of firms with low or no female board representation, which is consistent with historical gender gaps in EU corporate governance. Overall, the kernel distribution results affirm that the variables do not show severe departures from normality, supporting the use of parametric techniques for the empirical analysis.

4.3. Correlation Matrix and VIF Values

Table 4 presents the Pearson correlation coefficients and VIF values, offering initial insights into the relationships among variables and confirming the absence of multicollinearity. A modest but statistically significant positive correlation between carbon emissions (CO_2) and leverage (Lev) ($r = 0.048$, $P < 0.01$) suggests that higher-emitting firms may rely more on debt, potentially due to increased capital needs or reduced access to equity financing. Leverage is negatively correlated with ROA ($r = -0.194$), liquidity ($r = -0.403$), and capitalization ($r = -0.630$), aligning with pecking order theory, while it is

Figure 3: Kernell distribution of variables

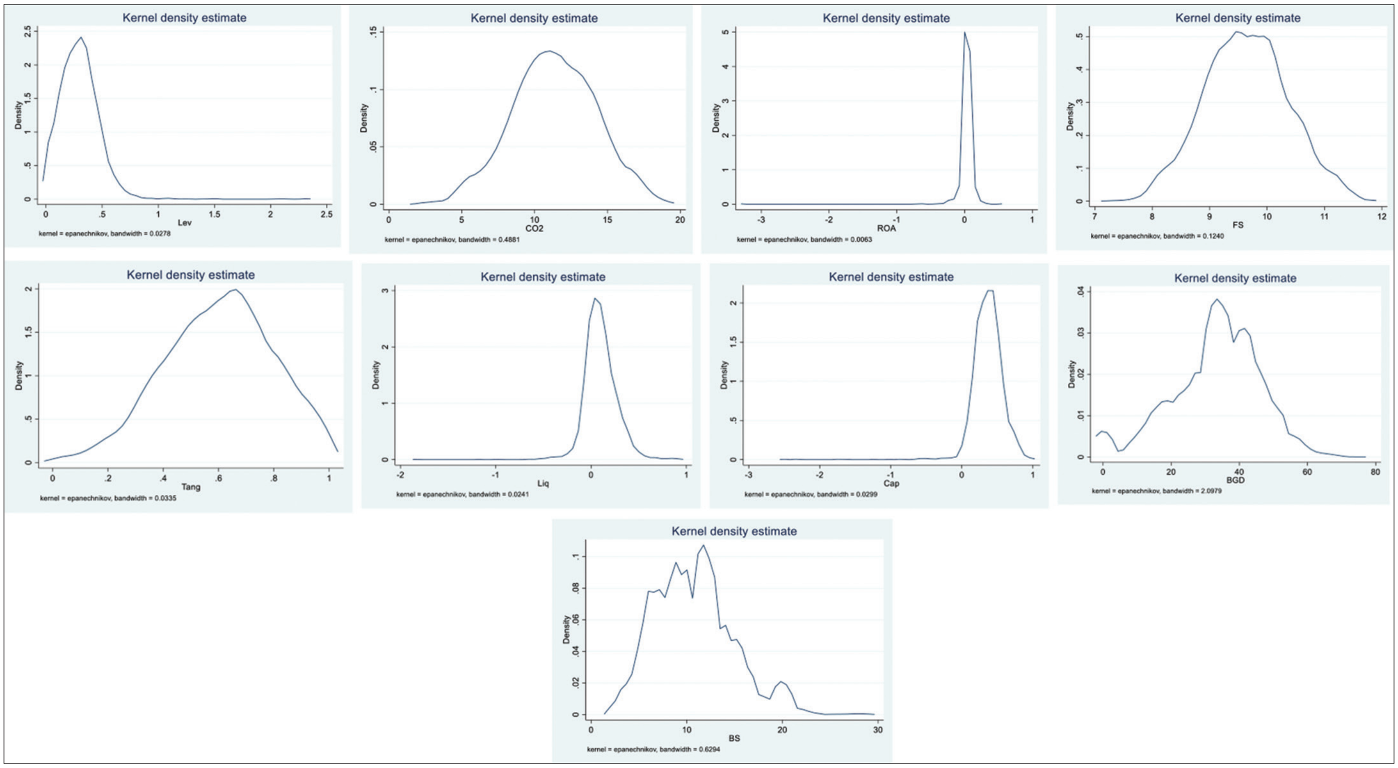


Table 2: Descriptions of variables

Variable	Abbreviation	Measurement	Source
Dependent variables			
Leverage	Lev	The ratio of total debt to total assets.	LSEG (Datastream)
Independent variable			
CO_2 equivalent emissions total	CO_2	The natural log of total Carbon dioxide (CO_2) and CO_2 equivalents emission.	LSEG (Datastream)
Control variables			
Return on assets	ROA	Return on assets = net income divided by total assets	LSEG (Datastream)
Firm size	FS	The natural log of total assets of a firm.	LSEG (Datastream)
Tangibility	Tang	(the ratio of tangible assets to total assets)	LSEG (Datastream)
Liquidity	Liq	Liquidity = (current asset - current liabilities)/total assets	LSEG (Datastream)
Capitalization	Cap	Equity capital divided by total assets.	LSEG (Datastream)
Board gender diversity, percent	BGD	Percentage of female on the board.	LSEG (Datastream)
Board size	BS	The total number of board members at the end of the fiscal year.	LSEG (Datastream)

Table 3: Descriptive statistics

Variables	Observations	Mean	Standard deviation	Median	Min	Max
Panel A: Dependent variables						
Lev	4183	0.30	0.18	0.29	0.00	2.33
Panel B: Independent variable						
CO_2	4183	11.35	2.87	11.33	1.95	19.09
Panel C: Control variables						
ROA	4183	0.03	0.09	0.04	-3.29	0.55
FS	4183	9.64	0.73	9.63	7.24	11.78
Tang	4183	0.60	0.20	0.61	0.00	1.00
Liq	4183	0.10	0.17	0.09	-1.85	0.94
Cap	4183	0.37	0.21	0.37	-2.53	0.99
BGD	4183	33.10	13.00	33.33	0.00	75.00
BS	4183	10.73	4.07	11.00	2.00	29.00

This table shows descriptive statistics for the variables used in this study. In Panel A, the dependent variables include Lev. In Panel B, the independent variable is CO_2 and Panel D is a comprehensive set of control variables. Our sample includes a total of 4,183 firm-year observations at Firm-year from 2010 to 2024

positively correlated with tangibility (r = 0.378), indicating the importance of collateral in debt access (Rodriguez, 2024). CO_2 emissions are strongly correlated with firm size (r = 0.669), and moderately with tangibility (r = 0.168) and board size (r = 0.470), reflecting the operational and structural scale of larger firms. Board gender diversity (BGD) shows weak and statistically insignificant correlations with most variables, including leverage (r = −0.013), indicating minimal direct influence on capital structure. All VIF values fall below 3, confirming no multicollinearity concerns and validating the model's suitability for regression analysis.

4.4. Unit-Root Test

Table 5 presents the results of the Fisher type unit-root test applied to all variables to assess their stationarity properties. The P-values for all variables including leverage (Lev), carbon emissions (CO_2),

Table 4: Correlation matrix and VIF values

Variables	Lev	CO_2	ROA	FS	Tang	Liq	Cap	BGD	BS	VIF
Lev	1									
CO2	0.048***	1								1.93
ROA	−0.194***	−0.016	1							1.07
FS	0.074***	0.669***	0.008	1						2.46
Tang	0.378***	0.168***	−0.031**	0.302***	1					2.27
Liq	−0.403***	−0.151***	0.138***	−0.303***	−0.584***	1				2.93
Cap	−0.630***	−0.145***	0.239***	−0.151***	0.083***	0.503***	1			2.02
BGD	−0.013	0.002	0.014	0.163***	0.018	−0.113***	−0.02	1		1.07
BS	0.035**	0.470***	−0.007	0.570***	0.120***	−0.193***	−0.166***	0.132***	1	1.54

This table represents the correlation matrix and VIF values ***P<0.01, **P<0.05, *P<0.1

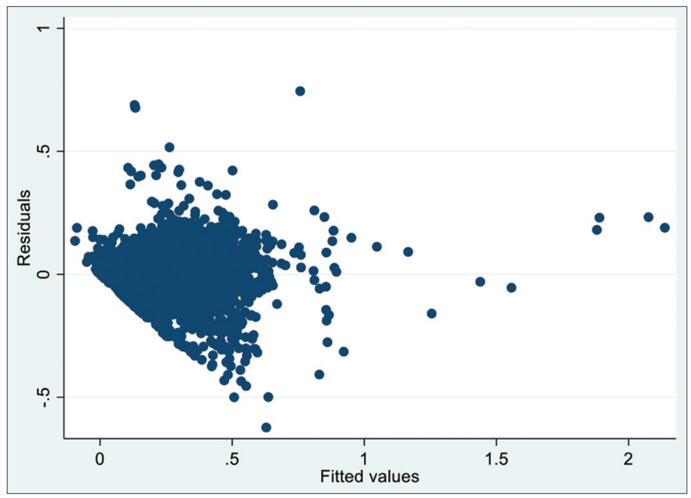
Table 5: Fisher-type unit-root test

Variable	P-value	Inference
Lev	0.0000	Stationary
CO_2	0.0000	Stationary
ROA	0.0000	Stationary
FS	0.0000	Stationary
Tang	0.0000	Stationary
Liq	0.0000	Stationary
Cap	0.0000	Stationary
BGD	0.0000	Stationary
BS	0.0000	Stationary

Table 6: Breusch-Pagan/Cook-Weisberg test for heteroskedasticity

Model	Chi2 (1)	Prob>Chi2	Inference
Model 1	321.07	0.0000	Heteroskedasticity

Figure 4: Residuals versus fitted values plot



and the full set of financial and governance control (De Rosa et al., 2024) variables are statistically significant at the 1% level ($P = 0.0000$), leading to the rejection of the null hypothesis of non-stationarity. This confirms that all variables are stationary in levels and do not exhibit unit roots. Stationarity is a critical assumption in panel data regression, as non-stationary variables may lead to spurious results and unreliable inferences. The confirmation of stationarity across all variables ensures the robustness (Ullah et al., 2021) of the regression model and supports the validity of using fixed-effects panel estimation techniques in the subsequent analysis.

4.5. Heteroskedasticity Test

Table 6 reports the results of the Breusch-Pagan/Cook-Weisberg test for heteroskedasticity applied to Model 1. The test yields a Chi-squared statistic of 321.07 with a $P = 0.0000$, leading to the rejection of the null hypothesis of homoskedasticity. This confirms the presence of heteroskedasticity in the regression residuals, indicating that the error (Oyekale, 2017) variance is not constant across observations. Supporting this, Figure 4, which plots residuals against fitted values, visually reinforces the test result. The spread of residuals increases with the fitted values, a classic pattern indicative of heteroskedasticity. Such non constant error variance violates the classical assumptions of OLS regression and may lead to inefficient coefficient estimates and biased standard errors if not addressed. To ensure robust inference, all regression models in the following section are estimated using heteroskedasticity-robust standard errors, which correct for this issue and maintain the validity of hypothesis testing in the presence of heteroskedasticity.

4.6. Regression-Analyses

Table 7 displays the regression outcomes estimating the impact of carbon emissions (CO_2) on firm leverage (Lev), using Ordinary least squares (OLS), fixed effects (FE), and System Generalized Method of Moments (System-GMM). All models account for year and industry fixed effects, (López-Manuel et al., 2023) with robust standard errors applied. Across all specifications, CO_2 emissions (CO_2) show a consistently negative and statistically significant effect on leverage. The coefficients range from −0.00284 (OLS) to −0.00371 (System-GMM), all significant at the 1% level. This suggests that higher-emitting firms tend to reduce their reliance on debt, possibly due to heightened regulatory risk, reputational pressure, or restricted access to financing in the EU context. In the dynamic GMM model, the lagged leverage term is positive and significant (0.397), reflecting strong persistence in firms' capital structure. Firm size (FS) has a negative and significant relationship with leverage across all models, indicating that larger firms tend to rely more on internal funding. In contrast, tangibility (Tang) and liquidity (Liq) show positive effects, suggesting that firms with greater asset backing and short-term solvency have stronger debt capacity. Capitalization (Cap) consistently displays a negative association with leverage, confirming that highly equity-financed firms require less debt. Board gender diversity (BGD) is weakly positive in OLS but becomes insignificant in GMM, indicating minimal direct impact once endogeneity is addressed. Board size

Table 7: Impact of CO_2 on Lev

Variables	(1)	(2)	(3)
	OLS	FE	GMM
	Lev	Lev	Lev
Lag of Lev	-	-	0.397***
	-	-	−0.0506
CO_2	−0.00284***	−0.003**	−0.00371***
	(0.00)	(0.00)	(0.00)
ROA	0.000342	−0.0000684	−0.0346
	(0.02)	(0.01)	(0.06)
FS	−0.0260***	−0.027***	−0.0201**
	(0.00)	(0.01)	(0.01)
Tang	0.711***	0.387***	0.541***
	(0.01)	(0.02)	(0.09)
Liq	0.538***	0.24***	0.410***
	(0.02)	(0.01)	(0.08)
Cap	−0.818***	−0.841***	−0.572***
	(0.01)	(0.01)	(0.06)
BGD	0.000297**	0**	0.0001
	(0.00)	0.00	(0.00)
BS	−0.00134***	0.001*	−0.000155
	(0.00)	(0.00)	(0.00)
Controls (Year dummies)	Yes	Yes	Yes
Controls (industry dummies)	Yes	Yes	Yes
Constant	0.394***	0.608***	0.257***
	(0.03)	(0.08)	(0.06)
Observations	4183	4183	3260
R-squared	0.72	0.687	-
Adjusted R^2	0.7183	0.608	-
Hausman P value	-	0.000	-
AR1 P value	-	-	0.001
AR2 P value	-	-	0.06
Hansen P value	-	-	0.335
Sargan P value	-	-	0.121

This table reports the regression results for model. From 2010 to 2024, the correlation between CO_2 and Lev and the other control variables is examined. Column 1 represents the OLS regression results, column 2 represents the Fixed effects regression results and column 3 represents the System-GMM regression results after controlling for the year and industry fixed effect to capture heterogeneity. The standard errors are reported in parentheses. ***, **, * denote significance at the 1%, 5% and 10% level, respectively

(BS) has a small negative effect in OLS but no significant impact in GMM, possibly due to firm-specific differences in governance. The GMM diagnostics confirm model validity. The AR (1) test shows expected serial correlation (P = 0.001), while AR (2) (P = 0.06) and the Hansen (P = 0.335) and Sargan (P = 0.121) tests confirm no over-identification concerns.

4.7. Robustness Test

To verify the consistency of the primary findings, a robustness check was performed by segmenting the sample based on firm size. Table 8 reports System-GMM regression estimates for two subsamples: firms below the average firm size ("small firms") and those equal to or above the average ("large firms"). This analysis helps assess whether the emissions–leverage relationship varies by firm scale, recognizing that environmental exposure and financial strategies may differ across firm types. For small firms, CO_2 emissions have a negative coefficient (−0.00278), but the effect is statistically insignificant. This implies that emissions do not significantly influence leverage decisions among smaller firms (Shi and Yao, 2025), possibly due to lower regulatory exposure or limited visibility in ESG-focused financing markets.

Table 8: Impact of CO_2 on Lev (Small firm and Large firms)

Variables	(1)	(2)
	GMM	GMM
	W	W
Lag of Lev	0.312***	0.571***
	(0.06)	(0.07)
CO_2	−0.00278	−0.00430**
	(0.00)	(0.00)
ROA	−0.00615	−0.203***
	(0.04)	(0.05)
FS	−0.0300**	−0.00823
	(0.01)	(0.01)
Tang	0.649***	0.336***
	(0.15)	(0.10)
Liq	0.492***	0.245***
	(0.14)	(0.09)
Cap	−0.648***	−0.381***
	(0.08)	(0.07)
BGD	0.000454	−0.000321
	(0.00)	(0.00)
BS	0.00231	−0.00172
	(0.00)	(0.00)
Controls (Year dummies)	Yes	Yes
Controls (industry dummies)	Yes	Yes
Constant	0.289***	0.204**
	(0.11)	(0.09)
Observations	1559	1611
AR1 P value	0.029	0.0000
AR2 P value	0.061	0.08
Hansen P value	0.895	0.66
Sargan P value	0.664	0.146

Regression results from the model appear in this table. The relationship between CO_2 and Lev with other control variables was analyzed covering the years 2010 to 2024. Column 1 shows System-GMM regression results on observations for the small firms with sizes below the average FS; whereas in column 2, we have System-GMM regression results on observations for large firms with sizes equal or above the average FS. Industry fixed effects and year effects were adjusted, allowing for heterogeneity. The standard errors are reported in parentheses. ***, **, * denote significance at the 1%, 5% and 10% level, respectively

However, for large firms, the coefficient on CO_2 emissions is negative and statistically significant at the 5% level (−0.00430), indicating that high-emitting large firms actively reduce their debt exposure, likely in response to greater climate related financing constraints or reputational risks. The dynamic nature of capital structure is evident in both subsamples, with the lagged leverage variable being positive and significant (0.312 for small firms and 0.571 for large firms), reflecting persistence in debt policies. Among control variables, (Butt, 2020) ROA is strongly negative and significant only for large firms, suggesting profitability plays a larger role in leverage decisions in this group. Tangibility and liquidity are positive and significant across both groups, consistent with the idea that asset-based collateral and financial flexibility promote debt usage. Capitalization remains negatively related to leverage, as expected. Diagnostic tests confirm the robustness of the GMM estimations. AR (2) P-values (0.061 and 0.08) suggest no second-order serial correlation, and both Hansen and Sargan tests support instrument validity. These results reinforce the study's main conclusion that the negative impact of carbon emissions on leverage is more pronounced among larger firms, where environmental visibility and policy exposure are greater.

5. CONCLUSION AND POLICY IMPLICATIONS

Carbon emissions versus leverage for the companies this paper studies the 819 publicly listed EU companies from 2010 to 2024. Making use of a powerful dynamic panel data analytical setup (System-GMM) augmented by fixed effects and OLS models, the study has evinced a on-the-average statistically significant negative relation between carbon emissions and financial leverage. The findings indicate that firms generating higher CO_2-equivalent emissions prefer to maintain lower debt ratios (Ning et al., 2025), a phenomenon that is further exacerbated for larger firms. This makes climate-related risks a more conspicuous element in the decision-making regarding the capital structure of firms as companies do what they can to lessen the potential of reputational exposure, regulatory scrutiny, and borrowing constraints in an ESG-conscious financial world.

This test returns demonstrate the flow of this binding crossroad between environmental accountability and financial strategy. The more so, firm-specific financial fundamentals such as profitability, tangibility, liquidity, and capitalization still exert decisive influence (Vengesai, 2023) on debt behavior. Governance measures like board size and gender diversity showed very little impact on emissions enhancement, but their role in wider sustainability- and transparency-related mechanisms cannot be ignored. Hereafter, the presence or absence of heteroskedasticity reinforces the heterogeneous nature of the emissions-leverage nexus inter-industries and across time periods.

Given the implications, EU policymakers should, therefore, incorporate emissions performance at the firm level into sustainable-finance taxonomies and credit risk appraisal. More aggressive regulations advocating for carbon disclosure and broad-based issuance of green instruments, including transition-linked loans and sustainability-linked bonds, shall empower capital markets to more efficiently penalize behavior leading to high emissions. In addition, corporate boards and CFOs are encouraged to consider carbon risk as a new form of financial risk. From this principle, investment strategies in emissions abatement, combined with transparent ESG reporting, should channel positive outcomes both environmentally and financially through enhanced credit ratings and long-term financial resilience.

The focus of subsequent research should be on cross-sectoral differences within the relationship and on how evolving EU climate policies (i.e., CBAM, EU Green Deal, and Fit for 55) shape capital structure choices. The comparative studies between OECD and non-OECD areas would shed further light on the extent to which decarbonization imperatives globally converge with financial strategies, thereby specifying routes for climate-aligned financial systems.

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