

Does Carbon Transparency Pay Off? A Long-Horizon Portfolio of Post-Disclosure Performance

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Abstract

This study investigates whether enhanced carbon transparency leads to improved long-term, risk-adjusted performance for European equity portfolios. Using a unique nine-year panel of 315 firms and a sector-neutral, multi-factor empirical framework, we find that while return patterns are consistent with a market preference for firms with lower emissions, decarbonization, and robust environmental policy disclosure, these features do not generate persistent “greenium” once traditional risk factors and structural effects are taken into account. Across multiple portfolio constructions and rigorous cross-sectional regressions, the incremental benefits of transparency and decarbonization remain modest and highly context-dependent. Our findings suggest that the progressive harmonization of ESG reporting—in the EU—has contributed to a high degree of informational efficiency, with carbon risk now largely internalized in asset prices. As a result, the principal value of transparency lies in risk management and regulatory alignment, rather than in systematic financial out-performance. These results highlight both the achievements and limitations of the EU’s evolving sustainable finance agenda, underscoring the need for future research as disclosure standards continue to mature.

JEL codes: G11, G14, G18, Q52, Q56

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Introduction

Management of portfolio risk and performance has undergone a fundamental transformation in response to growing concerns about climate change and carbon emissions. With the adoption of the Paris Agreement in 2015, international financial markets have progressively acknowledged the material financial implications associated with greenhouse gas (GHG) emissions and related climate risks (Bolton & Kacperczyk, 2021; Sautner et al., 2020). In particular, carbon emissions are now widely recognized as key indicators of firm-specific risk, influencing investors' risk-adjusted return expectations and portfolio allocation strategies (Oestreich & Tsiakas, 2015).

In parallel with these developments, the regulatory landscape in Europe has evolved rapidly, driven by a series of directives including the Sustainable Finance Disclosure Regulation (SFDR), the EU Taxonomy for Sustainable Activities, and more recently, the Corporate Sustainability Reporting Directive (CSRD). These initiatives aim to standardize and enhance transparency of corporate carbon emissions disclosures, facilitating informed investment decisions and improved risk assessment by market participants (Ioannou & Serafeim, 2012; Dutta et al., 2018; Hong, Li & Xu, 2019). The introduction of the International Sustainability Standards Board (ISSB) further underscores the global ambition to harmonize sustainability reporting, particularly concerning the quality, reliability, and comparability of corporate GHG data.

Despite extensive documentation on the relationship between carbon emissions and firm-level risks (Hong & Kacperczyk, 2009; Bolton & Kacperczyk, 2023a), comparatively little attention has been paid to how explicit differences in transparency regarding corporate GHG emissions affect long-term portfolio performance. Most of the existing literature remains concentrated on broad ESG metrics or aggregated measures of carbon intensity, thus neglecting nuanced distinctions in disclosure transparency standards (Bolton & Kacperczyk, 2021). Consequently, the critical question of whether enhanced transparency in emissions reporting leads to superior risk-adjusted portfolio returns over a long-term horizon remains largely unexplored. Our article explicitly addresses this gap by empirically evaluating the performance of equity portfolios rebalanced according to distinct levels of carbon disclosure transparency and the carbon performance associated with that relative to the sector for the firm.

More precisely, this study investigates the extent to which greater transparency in corporate GHG emissions disclosure allows European firms to deliver superior risk-adjusted financial performance compared to less transparent peers. Using a robust empirical framework based on portfolio sorting techniques and Fama-French factor models, we explicitly examine whether transparency related to carbon emissions acts as an effective signal to investors, thus improving portfolio returns and reducing exposure to long-term climate transition risks (Oestreich & Tsiakas, 2015; Andersson, Bolton & Samama, 2016).

From an investor’s perspective, these insights are particularly timely given the increasingly stringent regulatory context in Europe. The EU’s Green Deal ambitions mandate significant carbon reductions, aiming for net-zero emissions by 2050. Regulatory measures such as CSRD and SFDR not only require companies to report their greenhouse gas emissions comprehensively, but also implicitly suggest that firms exhibiting greater transparency are likely to be better positioned to manage regulatory transition risks (Hong, Li & Xu, 2019; Girerd-Potin, Jimenez-Garcès & Louvet, 2017). Understanding how markets price transparency into equity valuations can therefore offer asset managers and institutional investors critical insights for portfolio allocation and risk management strategies.

In addition, sector-level distinctions represent another critical dimension for investors. Carbon-intensive industries—such as energy, manufacturing and transportation—are inherently more exposed to transition risks and regulatory scrutiny, potentially influencing the perceived value of transparency in emissions disclosures (Hong & Kacperczyk, 2009; Bolton & Kacperczyk, 2023a,b). Although our primary focus remains on the financial implications of carbon-disclosure transparency among European firms, we recognize that its relevance is unlikely to be uniform across contexts. Because transition risks, regulatory pressure, and investor expectations differ markedly across industries, the perceived value of transparency may vary substantially from one sector to another. Similarly, cross-country differences in policy ambition and climate sensitivity can shape how markets interpret and disclose prices. Accounting for these sources of heterogeneity is therefore essential to interpret carbon transparency as an economically meaningful signal.

Methodologically, our empirical analysis unfolds through two complementary steps. Initially, we construct and rebalance equity portfolios based explicitly on the carbon levels of transparent firms, as disclosed in their carbon reports, and evaluate their performance using the Fama-French five-factor model. Subsequently, we perform a cross-sectional analysis of firm-level alphas to determine whether transparency consistently translates into improved long-term risk-adjusted returns, explicitly controlling for country and sector fixed effects. This dual approach enables us not only to quantify the direct financial implications of enhanced transparency but also to examine the robustness of these findings across various regulatory and sectoral contexts.

In fine, this article addresses a central research question: does transparency in carbon emission disclosures significantly influence long-term portfolio performance through reduced perceived transition risks? By explicitly focusing on transparency in emissions disclosure, our research contributes to a more nuanced understanding of how tangible ESG metrics can meaningfully guide investor decisions and asset allocation within the contemporary regulatory landscape.

1 Literature review

A large and growing body of research documents the financial implications of corporate carbon emissions, showing that market valuations increasingly incorporate greenhouse-gas exposure into asset pricing and risk assessment (Bolton & Kacperczyk, 2021, 2023a, b; Matsumura, Prakash, & Vera-Muñoz, 2014). Mounting empirical evidence points to a positive relationship between robust carbon management and reduced capital cost, alongside improved firm valuation, driven primarily by decreased investor uncertainty about future regulatory risks and reputational exposure (Bolton & Kacperczyk, 2021, 2023b; Matsumura et al., 2014). Nevertheless, predominant studies largely employ aggregate ESG ratings or broad environmental indicators derived from heterogeneous scoring systems, yielding limited consistency and considerable ambiguity for investors (Berg, Kölbel, & Rigobon, 2022; Billio, Costola, Hristova, & Pelizzon, 2019; Benlemlih, Jaballah, & Peillex, 2018). These rating discrepancies create significant barriers to consistent ESG risk pricing (Gibson et al., 2022; Serafeim & Yoon, 2023) and complicate investor comparisons of corporate sustainability profiles (Windolph, 2011; Edmans, 2023; Flammer, 2023).

Driven by increasing regulatory expectations and market pressures, Corporate Social Responsibility (CSR) has progressively evolved from qualitative commitments toward explicit, quantifiable ESG metrics, underscoring the financial materiality of sustainability (Freeman, 1984; Flammer, 2013; Liang & Renneboog, 2017). However, persistent divergences among ESG ratings providers, as highlighted by Berg et al. (2022) and Billio et al. (2019), fuel growing skepticism regarding their reliability and investor relevance. Addressing these criticisms, recent scholarship argues that focusing explicitly on quantitative, transparent carbon metrics—such as Scopes 1, 2, and 3 emissions, and year-over-year changes—provides clearer, more robust signals for portfolio managers aiming to mitigate greenwashing risks and achieve genuine sustainability performance (Edmans, 2023; Flammer, 2023; Aswani, Raghunandan, & Rajgopal, 2024).

Carbon emissions have gained particular traction among investors due to their direct climate implications and relative methodological consensus offered by frameworks such as the GHG Protocol (Cornell, 2021; Alessi, Battiston, Melo, & Roncoroni, 2020). Explicitly linking emissions with financial liability, carbon pricing mechanisms underscore the tangible economic consequences faced by high-emitting firms (Bancel & Philippe, 2021; Chava, 2014; Nordhaus, 2019; Garveya, Iyera, & Nashb, 2018). Empirical evidence from Matsumura et al. (2014) and In, Park, & Monk (2019) similarly highlights the detrimental impacts of carbon intensity on firm value. Nevertheless, the robustness of the link between emissions and subsequent returns remains debated; for instance, Bolton & Kacperczyk (2023a) and Aswani et al. (2024) caution that the relationship between lower emissions and higher returns might be nuanced and context-dependent.

Despite these advances, the scholarly corpus devoted to portfolio strategies explicitly centered on verifiable carbon metrics is still in its nascent stage. While several seminal papers, such as those by Pedersen, Fitzgibbons, & Pomorski (2021), Chiu, Hsu, Li, & Tong (2024), and Kruse, Mohnen, Sato, & Pope (2020), investigate ESG integration broadly, few systematically explore portfolios dynamically constructed and periodically rebalanced based explicitly on transparent carbon metrics. Notable exceptions include Engle et al. (2020) and Görgen et al. (2020), who propose climate risk factors constructed from firm-level environmental exposures. Likewise, Pastor, Stambaugh, & Taylor (2021, 2022) underscore how investor preferences shape long-term valuation premiums for sustainable investments, yet again utilizing broad-based ESG criteria rather than firm-specific carbon metrics.

In addition, the transition risk perspective remains critical for portfolio management, highlighting potential valuation impacts for companies failing to reduce emissions or adequately adapt to evolving carbon regulations and market expectations (Andersson, Bolton, & Samama, 2016; Bolton, Halem, & Kacperczyk, 2022). Notably, Hartzmark & Shue (2023) and Edmans et al. (2023) argue in favour of strategic portfolio tilts rather than complete divestment, underscoring how nuanced capital allocation can simultaneously incentivize genuine emissions reductions and minimize unintended adverse market effects. This result aligns with the broader literature advocating active ESG engagement strategies to drive long-term sustainability outcomes while maintaining competitive risk-adjusted returns (Gantchev, Giannetti, & Li, 2024; Spyros & Drosos, 2024; Ilhan, Sautner, & Vilkov, 2021; Serafeim & Yoon, 2023).

Finally, strong carbon performance, characterized by credible disclosures and substantial emissions reductions, helps mitigate information asymmetries and investor uncertainty, thus reducing required risk premiums (Gompers, Ishii, & Metrick, 2003; Depoers, 2021; Viviani, Touchais, & Nguyen, 2022). Although achieving consistently positive valuation effects across Europe remains challenging due to variations in stakeholder pressures and institutional frameworks (La Porta et al., 1998), robust carbon transparency consistently emerges as a reliable signal of future corporate performance (Benlemlih & Girerd-Potin, 2017). Building on these insights, we examine whether such signals translate into persistent differences in long-horizon risk-adjusted portfolio performance in European equity markets.

2 Conceptual framework

Corporate carbon emissions have increasingly become integral to investors' strategic decision making processes, extending beyond traditional environmental considerations to influence long-term financial risk management and portfolio optimization. Investors now perceive firm-level carbon emissions not merely as indicators of ecological responsibil-

ity but as critical metrics reflecting future regulatory exposure, financial liabilities, and broader market risk (Bolton & Kacperczyk, 2021, 2023a,b; Matsumura et al., 2014; Pastor et al., 2022). In particular, the transparency and credibility of carbon disclosures have become paramount, providing essential signals that help investors distinguish genuinely proactive firms from those engaging in superficial sustainability practices (Edmans, 2023; Serafeim & Yoon, 2023).

Underpinning investor reliance on carbon transparency is the canonical financial-economics view that credible, decision-useful disclosure is a first-order determinant of how markets form expectations and price risk. Ross’s (1977) and Merton’s (1987) insights into information asymmetry emphasize that markets reward firms providing clear, verifiable disclosures, reducing investor uncertainty. Specifically, transparent carbon metrics enable investors to better evaluate firm-specific risks associated with future regulatory changes and carbon pricing mechanisms (Orlitzky, 2013; Demaria et al., 2024). Investors thus prefer companies qualified to demonstrate credible emissions management, expecting that these firms will benefit from lower capital costs and improved long-term profitability due to diminished exposure to regulatory and reputational risks (Nordhaus, 2019; Garvey et al., 2018). This rationale motivates our first hypothesis:

- **H1:** Over the long term, portfolios comprising firms with lower carbon emissions outperform portfolios consisting of higher-emitting firms.

Beyond the static evaluation of current emissions, investors also critically assess the transparency with which firms communicate their emissions reductions over time. This dynamic aspect of disclosure is particularly significant given the tightening regulatory environment, notably under the Paris Agreement and the European Union’s evolving climate policies. Firms proactively disclosing their annual emission reductions not only demonstrate strategic adaptability but also align with increasing stakeholder demands for environmental accountability (Freeman, 1984; Bénabou & Tirole, 2010). Such transparent disclosures signal credible management strategies, alleviating investor concerns regarding future regulatory compliance costs and potential reputational risks (Edmans et al., 2022; Hartzmark & Shue, 2023). Accordingly, clear disclosure practices effectively serve as market signals, positioning firms favorably in the eyes of investors who prioritize long-term sustainable returns.

Equally influential is the theory of individual and corporate social responsibility developed by Bénabou & Tirole (2010), which provides an economic justification for integrating non-financial objectives—such as emission reductions—into portfolio construction. In this framework, investors may seek not only financial returns but also legitimacy and social impact, thereby legitimizing “tilt” or long-short strategies that overweight sustainable companies and penalize laggards. Disclosure transparency is approached through (i) a long-horizon universe with continuous emissions information available to investors (re-

ported when available, otherwise estimated), and (ii) the environmental policy disclosure, which proxies the breadth and credibility of disclosed environmental governance. Such methods are not merely ethical: they are rooted in the expectation that markets will reward credible improvements in carbon performance with valuation premiums and penalize opacity or stagnation.

- **H2:** Over the long term, portfolios composed of firms explicitly and transparently disclosing their carbon emissions outperform portfolios of less transparent firms.

Besides, investors increasingly recognize the significance of firms' sustained progress in emission reductions as a robust indicator of effective corporate governance and strategic foresight. Investors interpret continuous year-over-year reductions in carbon emissions as credible commitments to long-term sustainability, reflecting proactive management of transition risks and signaling future resilience against climate-related disruptions (Bolton et al., 2022; Andersson et al., 2016). Firms demonstrating persistent reductions in their emissions profiles benefit from reduced uncertainty and lower implied future risks, thereby gaining preferential positioning in investor portfolios seeking stable long-term returns (Avramov et al., 2022; Serafeim, 2020; Bruno et al., 2021). This logic motivates our third hypothesis:

- **H3:** Portfolios consisting of firms achieving consistent year-over-year reductions in carbon emissions outperform portfolios composed of firms without comparable reductions.

Moreover, it is essential to distinguish our approach clearly from existing practices within the ESG investment landscape. Traditionally, ESG strategies rely heavily on aggregated ESG scores or broad-based sustainability ratings from third-party providers, methodologies that have drawn criticism due to low inter-agency correlations and opaque assessment criteria (Berg et al., 2022; Billio et al., 2019; Flammer, 2023). In contrast, our study advocates for an explicit, data-driven approach utilizing firm-specific quantitative carbon metrics such as Scopes 1, 2, and 3 emissions, CarbonGap, and other regulated pollutants. By focusing directly on carbon data, our methodology, *ceteris paribus* offers investors a robust means to differentiate genuinely sustainable firms from those susceptible to accusations of greenwashing (Pedersen, Fitzgibbons, & Pomorski, 2021; Roncalli, 2024).

3 Methodology

The empirical design combines a long-horizon portfolio exercise with cross-sectional regressions.

3.1 Sample

Our universe begins with every firm classified as “Europe” in the Eurofidai ESG master file (just over 7,100 tickers). After merging with monthly return in LSEG Workspace we impose three continuity requirements:

1. Scope 1 and Scope 2 emissions—reported or estimated —must be available for each fiscal year from 2016 to 2024.
2. Monthly return, market value, leverage, ROE, and ICB codes must be non-missing over the same horizon.
3. The firm must be domiciled in an EU member state, Norway, or Iceland. The latter two have formally transposed the CSRD and pledged adherence to the Paris Agreement, providing an “EU-like” regulatory setting; that is why we decided to include them in the filtering process. In the end, only Norwegian companies were selected for the period.

The screen yields *315 listed firms*—roughly one in twenty of the initial candidates; indicating how scarce multi-year transparency remains even after the Paris Agreement. Retaining estimated values is crucial: investors observe them in real time (Engle et al., 2020), and excluding them would bias the sample toward already virtuous emitters.

Why focus on carbon emissions? Composite ESG ratings suffer from low inter-provider correlations and opaque weightings (Berg et al., 2022). Tonnes of CO₂ are observable, financially material, and map directly into future cash-flow exposures—precisely the type of state variable envisaged by pricing (Ross, 1976). Using emissions, therefore, mitigates “aggregate confusion” and green-washing (Edmans, 2023) while aligning with investors’ carbon-pricing expectations (Chava, 2014).

Positioning our work relative to the existing literature highlights several key innovations. Earlier contributions, such as Görden et al. (2020), introduced a cross-sectional carbon risk factor, while Engle et al. (2020) developed strategies to hedge climate news using textual sentiment scores. However, neither line of research tracks portfolio alphas over a long multi-year horizon nor examines the European post-Paris transition period, as EU sustainable-finance and disclosure rules gradually tightened and carbon information became increasingly priced.

In contrast, our approach constructs sector-neutral long-short portfolios based directly on firms’ reported emissions and on year-over-year changes—what we term the “CarbonGap.” We then rebalanced these portfolios at each fiscal year-end, covering nine full holding periods from 2016 through 2024. For each portfolio, we estimate risk-adjusted performance via the European Fama–French five-factor model over 108 months of returns, rigorously capturing long-term alpha. Crucially, our design also incorporates controls for

both national and sectoral differences in climate sensitivity, ensuring that any observed premium reflects genuine merit in carbon transparency rather than confounding structural factors. By uniting these elements, our sample and methodology are purpose-built to test whether credible, forward-looking emissions disclosures—instead of broad ESG sentiment—deliver a replicable reward to investors in European equity markets.

3.2 Risk-Adjusted Portfolio Returns

To rigorously assess whether transparent carbon disclosure and emission reductions are rewarded in European equity markets, we develop a systematic, multi-step portfolio construction methodology inspired by recent advances in sustainable investing research (Pastor, Stambaugh, & Taylor, 2021; G6rger et al., 2020). Our approach is purpose-built to eliminate common biases—such as sector composition and firm size—while isolating the genuine impact of carbon metrics on risk-adjusted returns.

A practical challenge in European emissions data is that firm-year observations are occasionally missing, even within otherwise continuous disclosure histories. Rather than dropping these firms or years—which would mechanically tilt the sample toward the most consistently reporting (and typically “cleaner”) issuers—we retain Eurofidai ESG observations recorded as “reported” whenever available and complement gaps with the corresponding “estimated” values. This choice is justified: investors price transition risk using the information set available at the time, which plausibly embeds sector benchmarks and peer comparisons that allow market participants to form expectations about unreported emissions. In that sense, estimated emissions proxy for the market’s own imputation of missing disclosures, and retaining them helps preserve the investable, real-time nature of the signals we study while limiting selection bias.

Step 1: Sector-Relative Ranking and Standardization. At each year-end (31 December, $t - 1$), we compile the most recent emissions data for all firms, calculating total carbon output as the sum of the natural logarithms of Scope 1, Scope 2, Scope 3, and other principal pollutants (NO_x , SO_x , VOCs):

$$\log(\text{EMCO2}_{i,t}) = \log(\text{Scope1}_{i,t}) + \log(\text{Scope2}_{i,t}) + \log(\text{Scope3}_{i,t}) + \log(\text{OP}_{i,t}), \quad (1)$$

where OP aggregates other pollutants and all emissions are sourced from Eurofidai ESG databases.

Recognizing the pronounced heterogeneity in carbon intensity across industries, we neutralize sector bias by standardizing each firm’s emissions relative to its ICB sector peers:

$$z_{i,t} = \frac{\log(\text{EMCO2}_{i,t}) - \mu_{s,t}}{\sigma_{s,t}}, \quad (2)$$

where $\mu_{s,t}$ and $\sigma_{s,t}$ represent the mean and standard deviation of log-emissions within sector s in year t .

Step 2: Portfolio Formation via Sector-Neutral Quintiles. Firms are then sorted within each ICB sector into five equal-weighted quintiles, from Q1 (lowest carbon intensity) to Q5 (highest carbon intensity). Equal weighting is deliberately chosen to eliminate size-related distortions (Pastor et al., 2021), and ensures that the observed return patterns are not simply a byproduct of capitalization effects.

Step 3: Annual Rebalancing and Out-of-Sample Construction. At the start of each calendar year t , portfolios are reconstituted based on the previous year’s standardized emissions data. This ensures that each holding period (2016–2024, i.e., 9 years, 108 months) is strictly out-of-sample and that rebalancing fully incorporates updated disclosures and market conditions. The annual rebalancing process can be formally described as:

$$P_{p,t} = \{i \mid z_{i,t-1} \in [\text{Quantile}_{p-1}, \text{Quantile}_p]\}$$

where $P_{p,t}$ is the membership set for portfolio p in year t .

Step 4: Calculation of Monthly Portfolio Returns. For each month m within year t , the portfolio return is calculated as the arithmetic mean of the returns of all constituent stocks:

$$R_{p,t,m} = \frac{1}{N_{p,t}} \sum_{i \in P_{p,t}} R_{i,t,m}, \quad (3)$$

where $R_{p,t,m}$ is monthly return (m) of portfolio p formed in year t , $R_{i,t,m}$ denotes the observed monthly return for firm i , and $N_{p,t}$ is the number of firms in portfolio p for year t .

Step 5: Multifactor Risk Adjustment—Fama–French Alpha Estimation. To ensure that observed outperformance is not merely compensation for standard risk exposures, we regress monthly portfolio excess returns against the five Fama–French European factors (Fama & French, 1993):

$$R_{p,m} - R_{f,m} = \alpha_p + \sum_k \beta_{p,k} F_{k,m} + \varepsilon_m,$$

where F_k are the European Fama–French¹

This procedure is conducted Alphas α_p over the entire 108-month window, as well as on rolling 36-month sub-periods to verify the persistence of alphas. All statistical inference

¹ $R_{p,m} - R_{f,m} = \alpha_p + \beta_{\text{MKT}}(R_{\text{MKT},m} - R_{f,m}) + \beta_{\text{SMB}}\text{SMB}_m + \beta_{\text{HML}}\text{HML}_m + \beta_{\text{RMW}}\text{RMW}_m + \beta_{\text{CMA}}\text{CMA}_m + \varepsilon_m$. market, size, value, profitability, and investment factors.

employs Newey–West(3) standard errors to account for serial correlation. The data for Fama-French comes from the Kenneth R. French Data Library

Step 6: Long–Short Portfolio Construction and Economic Interpretation. Our principal portfolio strategy exploits the difference in risk-adjusted performance between the most carbon-efficient and most carbon-intensive firms, defined as:

$$\alpha_{\text{LS}} = \alpha_{\text{Q1}} - \alpha_{\text{Q5}}.$$

As an illustrative example, if $\alpha_{\text{Q1}} = +2.5\%$ per annum and $\alpha_{\text{Q5}} = -3.2\%$, the long–short carbon alpha is $+5.7\%$, providing clear evidence of a “carbon transparency premium” for investors.

Step 7: Robustness—Bi-Dimensional Sorting and Environmental Policy Tilt.

To further interrogate the drivers of portfolio performance, we conduct two advanced robustness checks. Each follows the same annual formation, equal-weighting, and return computation as our baseline sector-neutral quintile methodology, but introduces additional, theoretically-motivated stratification.

First, we employ a bi-dimensional sorting procedure based on both carbon intensity and the direction of emissions change—capturing not only a firm’s position on the carbon spectrum, but also its trajectory. Within each ICB sector, all firms are initially ranked by carbon intensity, calculated as $\log(\text{EMCO2})$, and allocated to quintiles. Inside each carbon intensity quintile, firms are further subdivided according to their annual change in emissions (“CarbonGap”), which we define as:

$$\text{CarbonGap}_{i,t} = \frac{\text{EMCO2}_{i,t} - \text{EMCO2}_{i,t-1}}{|\text{EMCO2}_{i,t-1}|} \quad (4)$$

This secondary classification produces three groups—LowGap (substantial decrease), MidGap (stable), and HighGap (increase). Formally, for each sector s , the procedure is as follows:

$$\mu_s = \text{mean}(\log(\text{EMCO2})_{i,t}) \quad \sigma_s = \text{std}(\log(\text{EMCO2})_{i,t}) \quad z_{i,t} = \frac{\log(\text{EMCO2})_{i,t} - \mu_s}{\sigma_s}$$

Firms are sorted into quintiles based on $z_{i,t}$. Within each quintile, we further sort by $\text{CarbonGap}_{i,t}$ into terciles (LowGap, MidGap, HighGap). The final portfolios are constructed by intersecting these dimensions, such that, for each year t ,

$$P_{(p,q),t} = \left\{ i : z_{i,t-1} \in [Q_{p-1}, Q_p], \text{CarbonGap}_{i,t-1} \in [T_{q-1}, T_q] \right\} \quad (5)$$

where Q_p are quintile cutoffs and T_q are tercile cutoffs within each quintile. High-minus-low strategies are then formed across both intensity and change, thus capturing

not only the level but also the credibility of emissions reductions. This, therefore, better captures the level of decarbonization trajectory, closer to the “credibility premium” cited by Jiang, Kim, and Lu (2025).

Second, we implement an environmental policy tilt based on the POLENV disclosure score. Rather than modifying portfolio membership, this tilt systematically increases the weights of firms with higher environmental policy credibility, while keeping the overall investment universe unchanged. The tilting formula, adapting the approach of Pedersen et al. (2021), is:

$$w_{i,t}^{\text{tilt}} = \frac{w_{i,t}^{\text{eqw}} \cdot (1 + \Phi \cdot \text{POLENV}_{i,t})}{\sum_{j \in P_t} w_{j,t}^{\text{eqw}} \cdot (1 + \Phi \cdot \text{POLENV}_{j,t})} \quad (6)$$

where $w_{i,t}^{\text{eqw}}$ is the equal weight for firm i in portfolio P_t , and Φ governs the strength of the tilt towards policy disclosure. In this “beta-neutral” approach, the overall risk profile remains close to the original portfolio, but the allocation systematically favours companies with more robust environmental governance, reflecting the market’s preference for credible disclosure.

Both robustness analyses are executed using identical monthly return computations and risk-adjusted alpha estimation as our primary analysis, ensuring comparability. Together, these approaches enable us to determine whether not only emission levels, but also their year-over-year change and disclosure credibility, are consistently priced by markets.

Step 8: Evaluating Alpha Significance and Volatility. For all portfolio strategies—including baseline, bi-dimensional, and POLENV-tilted—we evaluate not only the magnitude but also the statistical significance (t-statistics) and ex-post volatility of the resulting alphas. This comprehensive assessment ensures that the observed performance is both economically meaningful and statistically robust.

This multifaceted portfolio construction methodology serves two fundamental purposes within the context of sustainable asset management. By leveraging both carbon intensity and its dynamic year-over-year change (CarbonGap), the approach transcends the limitations of static ESG scoring and directly tests whether markets reward not only “low-carbon” status, but also the momentum of decarbonization. In doing so, the bi-dimensional sorts and the policy tilt enable us to disentangle whether outperformance is primarily driven by structural low emitters or by firms demonstrating genuine improvement and environmental commitment over time. This distinction is essential for long-short strategies: it allows for the systematic identification of firms likely to deliver persistent alpha due to credible climate action, rather than temporary sectoral advantages or mean reversion.

Furthermore, the choice of the Fama–French five-factor alpha as the performance benchmark is particularly pertinent in this setting. By adjusting for classic risk premia

the estimated alpha isolates the component of returns attributable specifically to carbon disclosure and emission reductions, filtering out confounding exposures. As such, the resulting long-short portfolios represent investable, market-neutral strategies that are robust to factor risk and therefore more likely to reflect “true” sustainability premia. This empirical design offers a replicable and theoretically grounded pathway for asset managers to implement and evaluate climate-aligned investment strategies, while also contributing to the academic debate on the pricing of transition risk and the financial materiality of corporate decarbonization.

3.3 Cross-Sectional Regressions

To connect portfolio evidence with firm fundamentals, we regress nine-year Fama–French alphas α_i on emission variables:

$$\alpha_i = \beta_1 \text{CarbonGap}_i + \beta_2 \log \text{Scope1}_i + \beta_3 \log \text{Scope2}_i + \beta_4 \log \text{Scope3}_i + \beta_5 \log \text{OP}_i + \beta_6 \text{POLENV}_i + \mathbf{Z}'_i \boldsymbol{\gamma} + \varepsilon_i. \quad (7)$$

where $\mathbf{Z}_i$ bundles *Size*, *Leverage*, *Operating Margin*, *B/M*, *ROE*, country and industry dummies (*ICB*). All continuous variables are center-reduced (*z*-scored) for comparability.

- CarbonGap_i : year-on-year change in total emissions. Calculated as a relative variation.
- $\log \text{Scope1}_i$, $\log \text{Scope2}_i$, $\log \text{Scope3}_i$: logarithms of Scopes 1–3.
- $\log \text{OP}_i$: logarithm of NO_x , SO_x , VOC emissions.
- POLENV_i : six-point disclosure score indicating the presence of formal environmental policies (Eurofidai ESG) in the report.

Equation (7) is estimated using three complementary approaches. (i) We first run pooled OLS regressions with heteroskedasticity-robust HC3 standard errors. (ii) We then augment the specification with country and ICB industry fixed effects to absorb time-invariant institutional and sectoral heterogeneity in carbon exposure and asset pricing. (iii) To assess finite-sample uncertainty, we compute non-parametric bootstrap percentile confidence intervals based on 1,000 resamples at the firm level. In the APT spirit (Ross, 1976) and within the Bénabou–Tirole (2010) CSR framework, significantly negative estimates for β_{2-5} or a positive β_1 are consistent with markets pricing transition risk and (weakly) rewarding credible decarbonization.

The cross-sectional regression framework serves as an essential complement to the portfolio-based analysis by directly linking long-run risk-adjusted performance to granular firm-level carbon fundamentals and relevant controls. This approach enables us to

move beyond aggregate portfolio evidence and rigorously test whether transition risk is priced at the individual stock level, after accounting for sector, country, and classical financial determinants of returns. By incorporating variables, the model allows for nuanced attribution of alpha sources and a robust assessment of which factors drive persistent out-performance or penalty.

Moreover, the use of pooled OLS (with and without fixed effects) and bootstrap confidence intervals ensures that our findings are not artifacts of a specific model or sample period, but instead reflect systematic relationships within the European equity universe. This multi-pronged approach provides a powerful test of the hypothesis that carbon transparency and credible emissions reductions are financially rewarded—offering investors, policymakers, and researchers greater confidence in the robustness and generalization of our results

Data provenance and replication. Monthly returns, equity & accounting variables, and industry codes are sourced from *LSEG Workspace*. Carbon data and *POLENV* come from *Eurofidai ESG*, and Fama-French data come from *Kenneth R. French Data Library*. Details of the variables are available in Appendix 1.

4 Results

4.1 Variable description

Our final sample comprises 315 European firms, observed from 2016 to 2024, thereby offering a rich nine-year panel to analyze the evolving interplay between carbon transparency, firm fundamentals, and risk-adjusted portfolio performance. Table 1 presents descriptive statistics for all key variables, while Figure 1 displays their cross-correlations.

Risk-adjusted returns, captured by the Fama–French alpha, display a mean of -0.157 ($SD = 0.005$), with a median of -0.158 , suggesting that, on average, firms in our universe have slightly underperformed their theoretical risk benchmarks over the period. The relatively low standard deviation indicates a certain consistency in alpha outcomes across the sample.

Turning to carbon variables, log-transformed emissions across scopes display considerable cross-firm heterogeneity. For example, average direct emissions ($\log\text{Scope1}$) reach 10.24 ($SD = 3.28$), while indirect emissions ($\log\text{Scope3}$) are higher (mean = 13.19, $SD = 3.11$), underlining the significance of upstream activities in total carbon exposure. CarbonGap, which measures the relative annual change in emissions, averages 0.16 with a high standard deviation (2.62), reflecting wide divergence in decarbonization trajectories—some firms sharply reducing emissions, others stagnating or increasing.

Additional pollutants ($\log\text{OtherPolluants}$) and the environmental policy index (*POLENV*,

mean = 1.45, SD = 1.65) provide complementary perspectives on environmental disclosure breadth and governance practices. Notably, POLENV’s skewed distribution suggests that only a minority of firms report strong environmental commitments, despite rising regulatory pressure.

The control variables, crucial for disentangling pure carbon effects from firm fundamentals, display robust variability. Firm size (LogSize) clusters around a mean of 8.02, while leverage and profitability (OpMargin, LEV) vary substantially across firms and sectors. Book-to-market ratios (B/M) and return on equity (ROE) confirm this heterogeneity, supporting the need for careful risk adjustment and sector-neutralisation in all portfolio analyses.

Eventually, Figure 1 highlights several expected but non-trivial correlations: logScope variables are strongly interrelated, as are logOtherPolluants and direct emissions. Importantly, Alpha Fama–French is negatively correlated with emissions and firm size, indicating that higher-carbon, larger firms have—on average—underperformed their less-polluting, smaller peers, a result directly relevant for carbon-tilted portfolio strategies.

[Insert Table 1, Figure 1 here]

4.2 Risk-Adjusted Portfolio Returns

The evaluation of long-term, risk-adjusted portfolio performance constitutes the core of our study. We begin with the baseline sector-neutral quintile strategy, proceed to bi-dimensional intensity $\times$ CarbonGap sorting, and finally examine environmental policy tilting. Each approach offers a unique lens on how carbon metrics and governance transparency are integrated by European equity markets.

The first set of results, shown in Table 2, summarizes the performance of sector-neutral quintile portfolios, where firms are annually ranked within their ICB sector by standardized carbon intensity and allocated into five equal-weighted portfolios. The evidence is unambiguous: all quintile portfolios exhibit significantly negative annualized Fama–French alphas, with values ranging from -1.80% for low-carbon leaders (Q1) to -1.90% for high-carbon laggards (Q5). These alphas are all statistically significant at the 1% level, as confirmed by highly negative t -statistics. Despite this, the pattern in mean annual returns is informative: low-carbon portfolios consistently yield higher returns, with Q1 reaching 9.5% per annum (significant at the 0.1% level), while the most carbon-intensive quintile delivers negative returns. Taken together, these results provide clear empirical support for H1: portfolios composed of lower-emitting firms deliver higher mean returns than those of high emitters, even though the excess risk-adjusted performance (“greenium”) is not systematically positive once factor exposures are accounted for.

This gradient is consistent with the literature suggesting a market preference for firms with lower carbon footprints and echoes the risk-pricing intuition of Bolton & Kacperczyk (2021) and Pastor et al. (2021). However, the persistence of negative alphas, even among green leaders, underscores that risk-adjusted outperformance—the so-called “greenium”—remains out of reach for passive carbon-tilted strategies over a full market cycle. These results reinforce a core principle of modern asset pricing: sustainable investing alone does not guarantee abnormal returns once risks are properly accounted for (Fama & French, 1993; Bruno, Esakia, & Goltz, 2021).

[Insert Table 2 here]

A deeper examination is provided by the bi-dimensional portfolio sort based jointly on carbon intensity and the annual change in emissions (CarbonGap), as presented in Table 3. These findings also address H3, showing that portfolios built on firms with the most consistent year-over-year emissions reductions (low CarbonGap) systematically outperform, in mean returns, portfolios of less proactive peers, although once again the excess alpha remains modest after risk adjustment. This method enables us to identify not only firms that are currently low emitters, but also those that are persistently reducing their emissions—so-called “steady decliners”—as distinct from transitional laggards. The joint sorting delivers a clear monotonic structure: portfolios formed from the lowest intensity and lowest gap firms yield the highest mean annual returns (for example, Q1–LowGap: 10.2%), while those composed of high intensity and high gap firms fare the worst (Q5–HighGap: −0.97%). Alphas remain significantly negative across all cells, with values between −2.00% and −2.14% and strong statistical significance. These findings reinforce that while markets are attentive to both current carbon levels and the trajectory of emissions reduction, the magnitude of reward is insufficient to translate into persistent risk-adjusted outperformance. This confirms the conclusions of recent Jiang et al., 2025 & Edmans, 2023, which suggest that market recognition of credible transition strategies exists, but does not yet provide a systematic premium.

[Insert Table 3 here]

We investigate the impact of tilting portfolios toward firms with superior environmental policy governance, measured by the POLENV score, as detailed in Table 4. With regard to H2, our results indicate that greater transparency and robust environmental policy disclosure (as captured by higher POLENV scores) are associated with higher average returns, though the effect on risk-adjusted alpha is limited once standard factors are controlled for. Here, the same portfolio construction methodology is applied, but weights are adjusted to favor firms with above-median environmental policy disclosure. The results mirror those seen in previous approaches: negative alphas persist across all portfolios, yet mean returns are highest among portfolios tilted toward the highest POLENV scores

(Q1–Tilted: 8.8%, significant at the 0.1% level). This outcome underscores that markets do acknowledge the informational value of policy transparency and governance, echoing findings from Pedersen et al. (2021). However, as with intensity and reduction strategies, policy tilt alone does not unlock systematic alpha in the presence of robust risk adjustment.

[Insert Table 4 here]

All together, the results from all three portfolio construction methods converge on a consistent message. While there is clear evidence that investors reward firms for lower carbon intensity, credible reductions in emissions, and transparent environmental governance, these preferences are not sufficiently pronounced to generate persistent, market-beating risk-adjusted returns over the long term. This finding reinforces the “no free lunch” paradigm of modern portfolio theory, highlighting that the search for green alpha must reckon with both market efficiency and the increasing sophistication of investor expectations (Fama & French, 1993; Pastor et al., 2022; Bruno et al., 2021).

4.3 Long–Short Trading Strategies

In order to deepen our understanding of risk-adjusted outperformance linked to carbon transparency and emissions reduction, we investigate a suite of long–short trading strategies based on our portfolio constructions. By systematically exploiting the ranking structure across carbon quintiles, bi-dimensional sorts, and environmental policy tilts, we seek to uncover any persistent “greenium” or carbon premium available to active asset managers.

Our first analysis, in Table 5 (Long–Short—Sector Neutral Quintile), compares each lower-emission quintile (Q1–Q4) against those portfolios with higher carbon footprints (Q2–Q5). The resulting alpha differentials consistently demonstrate that taking a long position in the lowest-carbon portfolio (Q1—Green Leaders) and a short position in the highest-carbon quintile (Q5—Brown Laggards) generates the largest spread, at approximately 10.38 basis points per annum. Similar, but slightly lowered, *ceteris paribus*, positive alpha spreads are observed for other pairwise combinations (e.g., Q1–Q4, Q2–Q5), all indicating that, at the margin, carbon transparency and low emissions remain modestly rewarded. However, the magnitudes are economically small and suggest only limited exploitable abnormal returns in the cross-section.

[Insert Table 5 here]

Expanding on this, Table 6 (Long–Short—Bi-Dimensional Sorting) presents results for strategies that combine both carbon intensity and emissions trajectory (CarbonGap). Here, the largest alpha differences are observed when going long in low-intensity, declining

emitters (Q1-LowGap) and shorting high-intensity, rising emitters (Q5-HighGap), with spreads as high as 11.68 basis points per month. Nonetheless, the landscape of alpha differentials remains characterized by a preponderance of positive but economically modest values, reinforcing the conclusion that persistent excess returns for “green” strategies are limited. Negative spreads, when present, tend to be rare and statistically insignificant.

[Insert Table 6 here]

Turning to Table 7 (Long–Short—Tilt Environmental Policy), we evaluate the incremental effect of environmental policy disclosure by contrasting tilted portfolios (i.e., overweighting firms with POLENV 3). Once again, the alpha differentials favor the greenest tilted portfolios, with the Q1 Tilted and Q5 Tilted spread reaching nearly 9.54 basis points per month. The pattern remains consistent: long positions in high-transparency, policy-leading firms outperform short positions in their low-policy peers, but the realized premiums, though positive, do not point to large arbitrage opportunities after controlling for factor exposures and sector/country effects.

[Insert Table 7 here]

Overall, H1 and H3 are supported in terms of mean returns: lower-emitting firms and steady decliners exhibit higher average returns in sector-neutral sorts. However, none of the portfolio constructions delivers a positive and persistent risk-adjusted “greenium” once returns are benchmarked with the Fama–French five-factor model. Evidence for H2 is weaker: policy-disclosure tilts are associated with higher mean returns in some specifications, but do not generate robust long-horizon alpha after risk adjustment and structural controls.

Figures 2 and 3 visualize cumulative alpha and cumulative returns for key long–short portfolios. Figure 2 reports the cumulative alpha for the sector-neutral Q1–Q5 long–short strategy, while Figure 3 shows the cumulative alpha for the POLENV-tilted long–short.. In both cases, we observe that although the long–short spread remains slightly positive or flat over the entire sample horizon, neither strategy generates the type of persistent, escalating outperformance that would be expected of a robust greenium. Both the cumulative alpha and the return differentials highlight that the rewards for “green” tilts or carbon transparency, though directionally consistent with ESG theory (Pastor et al., 2021; Görgen et al., 2020), remain modest and are quickly arbitrated away in the competitive European equity landscape.

[Insert Figure 2, Figure 3 here]

Taken together, these results indicate that long–short strategies targeting low-carbon, transparent, or environmentally proactive firms do not, over the long run, produce persistent and economically meaningful risk-adjusted performance. This limited persistence

aligns with recent evidence from Mateus, Mateus, and Todorovic (2025), who emphasize that the identification of consistently superior financial performance remains challenging, even when employing sophisticated statistical frameworks and rigorous model specifications. Thus, investors seeking reliable long-term outperformance from carbon-based strategies may encounter structural limitations inherent to performance persistence itself. The absence of persistent risk-adjusted outperformance suggests that any pricing effects associated with carbon transparency and environmental policy leadership may be largely competed away once such information is broadly observed and incorporated into asset prices. This interpretation is consistent with recent asset-pricing evidence indicating that as ESG information becomes more fully reflected in valuations, any systematic greenium tends to dissipate unless new, material information arrives or persistent market frictions limit arbitrage (Bruno et al., 2021; Capelle-Blancard & Petit, 2019; Serafeim & Yoon, 2023).

4.4 Cross-Sectional Analysis: Determinants of Long-Term Risk-Adjusted Performance

This section investigates the fundamental drivers of long-term risk-adjusted performance (*alpha*) through a comprehensive cross-sectional regression framework. Our results, summarized in Table 8, provide a holistic perspective on the relationship between firm-level carbon metrics, environmental policy disclosure, and financial fundamentals. All specifications employ the Fama-French alpha as the dependent variable, computed over the full nine-year sample window, with robustness (bootstrap) assessed through alternative specifications and fixed effects.

The first set of regressions employs a standard pooled-OLS specification. Here, we observe that firm size (LogSize) emerges as the most consistently significant predictor of alpha, with a negative association across all Full specifications, in line with established asset pricing: larger firms tend to yield lower risk-adjusted returns. Profitability controls exhibit more limited and specification-dependent explanatory power: operating margin (OpMargin) remains statistically insignificant across Full models, while ROE becomes weakly to moderately significant once country and/or sector effects are absorbed. Across specifications, emissions-related variables—CarbonGap, the log-transformed Scopes 1–3, and other pollutants—enter with mostly negative point estimates, although statistical significance is generally limited in the Full models. This pattern is consistent with the transition-risk channel emphasized in the literature (Bolton & Kacperczyk, 2021, 2023a, b), but it also suggests that, once standard firm characteristics and structural effects are accounted for, the incremental cross-sectional association between emissions and long-horizon alpha is modest. In the parsimonious CarbonOnly specifications, however, Scope 2 and especially Scope 3 display more stable negative and sometimes significant coefficients,

indicating that the “carbon penalty” appears more clearly when financial controls are excluded.

The POLENV variable, capturing environmental policy disclosure, is not robust across specifications: it is negative and significant in the simplest CarbonOnly models, but the effect is largely absorbed once country fixed effects are introduced, and it becomes statistically insignificant in the most saturated specifications. Widespread, this result does not support a systematic “policy-disclosure premium” in long-horizon risk-adjusted performance at the firm level; rather, it suggests that cross-country institutional structure and sector composition explain much of the raw association, consistent with evidence that ESG information is increasingly competed away as it becomes widely observed and integrated into prices (Capelle-Blancard & Petit, 2019; Bruno et al., 2021; Serafeim & Yoon, 2023).

Introducing fixed effects for country and industry increases explanatory power in levels (R-squared rises), but adjusted fit remains broadly comparable across Full specifications, reflecting the trade-off between absorbing structural heterogeneity and the degrees-of-freedom cost of rich dummy structures. At the same time, the fixed-effects specifications highlight meaningful heterogeneity across sectors and countries: some industry categories (notably Utilities and, in several specifications, Energy) exhibit positive differentials. These patterns reinforce the broader message of the paper: European carbon-related performance is highly context-dependent, and country/industry structure can dominate firm-level carbon signals.

To further reinforce the reliability of our findings, we conduct a non-parametric bootstrap with 1,000 resamples for all coefficients in both pooled-OLS and fixed-effects models. Bootstrapped intervals are centered around the point estimates and generally confirm that most carbon and policy coefficients are not robustly different from zero once controls and fixed effects are included, while firm size remains the most stable predictor.

These results converge on a critical insight: while risk-adjusted returns (alphas) tend to be lower for higher-emitting firms, the magnitude of this penalty remains moderate and not uniformly robust once financial controls and structural country–industry effects are incorporated. In particular, CarbonGap is consistently close to zero and insignificant, while emissions levels (especially Scope 2 and Scope 3) display more systematic negative patterns in parsimonious specifications that attenuate as controls and fixed effects are added. Taken together, the evidence does not point to a persistent “greenium” in long-horizon risk-adjusted performance—an outcome consistent with both classic and recent work arguing that, as ESG metrics become widespread and increasingly standardized, any systematic premium is likely to dissipate in equilibrium (Bruno et al., 2021; Capelle-Blancard & Petit, 2019; Pastor et al., 2021; Serafeim & Yoon, 2023).

Together, *ceteris paribus*, our cross-sectional analysis provides additional support for the view that market participants price carbon transition risk, but it also cautions against

expecting stable excess returns from carbon transparency alone. In the European setting, the results suggest that country and industry context absorbs a substantial share of cross-sectional variation in long-run alpha, consistent with the sophistication and adaptability of capital markets in internalizing both environmental and financial risks over long horizons. Consequently, sustainable investment strategies built solely on carbon-related signals are unlikely to deliver persistent risk-adjusted outperformance absent new material information, regulatory discontinuities, or persistent frictions that limit arbitrage (Bruno et al., 2021; Capelle-Blancard & Petit, 2019; Pastor et al., 2021; Serafeim & Yoon, 2023).

[Insert Table 8]

5 Discussion

The findings of this study shed new light on the integration of carbon transparency within European equity markets and its implications for long-term portfolio management. Our analysis, spanning nearly a decade and grounded in sector-neutral portfolio construction, demonstrates that while investors display a clear preference for firms with lower emissions, credible decarbonization trajectories, and robust environmental policy disclosure, these characteristics do not systematically translate into persistent risk-adjusted outperformance once classic risk factors and structural effects are controlled for (Fama & French, 1993; Capelle-Blancard & Petit, 2019; Bruno et al., 2021).

The most salient result is the near-universal absence of a durable “greenium” across our portfolio and long-short strategies, even after exploiting granular carbon metrics, annual rebalancing, and advanced tilting schemes. Recent research by Parker and Engle (2025) has called attention to the methodological challenges in objectively ranking firms by their “greenness,” highlighting that, despite advances in carbon disclosure and data harmonization, investor perceptions and portfolio construction remain sensitive to model assumptions and disclosure nuances. Our findings, consistent with their conclusions, suggest that any attempt to systematically identify “the greenest” firms is complicated by ongoing data ambiguity and rapid evolution in disclosure practices. Our studies complement each other in the way that they focus on the US market, while we concentrate on the European market. This is consistent with modern asset pricing theory, as well as with empirical findings in the recent literature (Edmans, 2023; Pastor et al., 2021; Berg et al., 2022), which suggest that the competitive nature of financial markets quickly arbitrages away any systematic excess return linked to publicly available ESG or carbon information. The negative and often significant Fama–French alphas observed for both low- and high-carbon portfolios indicate that markets are highly efficient in incorporating available carbon risk information (Avramov et al., 2022; Flammer, 2023), leaving little room for sustainable alpha generation through transparent emissions management alone.

This is further reinforced by the cross-sectional regression analysis, where emissions variables are generally negative in sign but the link with long-horizon alpha is not robust once financial controls and country/industry fixed effects are introduced. In parsimonious CarbonOnly specifications, Scope 2 and Scope 3 emissions are more clearly associated with lower alpha, while the association of environmental policy disclosure (POLENV) is largely absorbed by country effects and becomes statistically weak in the most saturated models (Bolton & Kacperczyk, 2021, 2023a,b; Berg et al., 2022; Edmans, 2023; Serafeim & Yoon, 2023).

Several interpretations can be drawn from these results. First, the European equity landscape appears to have reached a state of advanced informational efficiency regarding carbon risk, particularly in the wake of regulatory tightening (SFDR, EU Taxonomy, CSRD) and increased investor sophistication (Ioannou & Serafeim, 2012; Dutta et al., 2018). The widespread integration of ESG data—both by asset managers and within reporting standards—has likely contributed to the swift neutralization of abnormal returns from simple transparency or carbon tilting strategies (Serafeim & Yoon, 2023; Gibson et al., 2022). As such, the empirical evidence aligns with theoretical models (Fama & French, 1993; Nordhaus, 2019) and recent studies (Bruno et al., 2021; Pastor et al., 2022), suggesting that any persistent outperformance linked to ESG integration will tend to diminish as markets become more adept at pricing both financial and non-financial risks (Billio et al., 2019).

Second, the absence of systematic alpha suggests that regulatory harmonization—such as the CSRD—may improve disclosure comparability and accelerate the incorporation of carbon information into prices, but it does not mechanically create an investable premium for transparent or proactive firms (Berg et al., 2022; Edmans, 2023). Rather, the market seems to distinguish between mere compliance and truly credible, transformative emissions reductions—a distinction only partially captured by available metrics and often diluted by sector, size, and country-specific effects (Pedersen et al., 2021; Bolton et al., 2022). The nuanced impact of the POLENV variable in our regressions, positive only when sector and country fixed effects are included, underscores that the benefit of transparency is not uniform, but contingent upon broader institutional and market settings (Gantchev et al., 2024).

Importantly, carbon characteristics can generate return differentials in some portfolio sorts and parsimonious specifications, but they do not translate into persistent, economically meaningful long-horizon risk-adjusted outperformance. In the cross-section, any emissions–alpha association is modest, specification-dependent, and attenuated once financial controls and country/industry effects are included (Hong & Kacperczyk, 2009; Matsumura et al., 2014; Ilhan et al., 2021; Pastor et al., 2021). The implication for asset managers is clear: carbon transparency and robust disclosure remain essential tools for managing transition risk and aligning portfolios with regulatory and societal objec-

tives, but they should not be mistaken for consistent sources of alpha in efficient markets (Andersson et al., 2016; Chava, 2014). For most investors, the principal benefit of such strategies may lie in improved risk management and reputational alignment, rather than in the promise of systematic financial outperformance (Freeman, 1984; Flammer, 2023).

A further implication arises from our robustness checks—both bi-dimensional sorting and environmental policy tilting. These methods confirm that more nuanced approaches to portfolio construction can better capture the complex interplay between emissions levels, their trajectory, and the credibility of environmental governance (Pastor et al., 2021; Jiang et al., 2025). However, even these advanced strategies do not overturn the basic finding that abnormal returns are arbitrated away in the current European context (Bruno et al., 2021; Serafeim & Yoon, 2023).

Several caveats must also be noted. First, our analysis is strictly limited to the European universe, *ceteris paribus*, where regulatory harmonization and ESG integration are especially advanced (Ioannou & Serafeim, 2012; Girerd-Potin et al., 2017). These findings may not be applicable to less mature markets or periods characterised by significant information shocks (Billio et al., 2019). Second, while our methodology leverages the most transparent and granular emissions data available, persistent issues of measurement error and strategic reporting, known as “greenwashing,” remain, particularly for Scope 3 and other indirect emissions (Berg et al., 2022; Aswani et al., 2024). Moreover, the importance of independent assurance in carbon accounting has been recently underscored by new research (Berg, Oliver Huidobro & Rigobon, 2025), which shows that third-party verification plays a critical role in enhancing the reliability and comparability of emissions disclosures. The absence or inconsistency of assurance mechanisms may further complicate investors’ ability to accurately price transition risks. Another limitation is the size of our sample, which is weighted to the data available in Europe over nine consecutive years.

In fine, the timing of our analysis—spanning the post-Paris Agreement years and the anticipation window for CSRD—may itself reflect a transitional phase (Viviani, 2024; Demaria et al., 2024). As European firms and investors fully adapt to CSRD-compliant reporting and as sustainability standards continue to evolve, new sources of alpha may emerge, especially if future disclosures prove more credible, comprehensive, and comparable (Edmans, 2023; Bolton & Kacperczyk, 2023b).

Future research could examine whether the full implementation of the CSRD alters the information environment enough to affect pricing dynamics and market liquidity in Europe (Roncalli, 2024; Serafeim & Yoon, 2023)

Conclusion

This study provides new empirical evidence on the financial implications of carbon transparency in European equity markets, offering a comprehensive assessment over a near-decade horizon and within the context of rapidly evolving regulatory standards. Our results indicate that, despite increasing investor attention to carbon disclosures and credible decarbonization strategies, transparent firms do not systematically generate persistent risk-adjusted outperformance once traditional risk factors and structural characteristics are fully accounted for.

The absence of a consistent “greenium” in both sector-neutral and long-short portfolio strategies underscores the efficiency of European markets in integrating carbon risk—an efficiency likely reinforced by the progressive rollout of regulatory initiatives such as the SFDR and CSRD. While lower-emission or better-disclosing firms can exhibit return differentials in some portfolio sorts, these patterns do not translate into persistent, economically meaningful excess returns once risk is properly accounted for. This is consistent with our cross-sectional regressions, where emissions-related effects are small and not robust across specifications, and any apparent role for policy transparency largely vanishes once country and industry structure is taken into account.

Importantly, our findings caution against simplistic expectations of durable alpha from ESG or carbon-tilted investment strategies in the current European setting. Instead, the principal value of robust carbon disclosure appears to lie in enhanced risk management, improved alignment with regulatory expectations, and reputational benefits rather than guaranteed financial outperformance. This nuanced reality requests that asset managers and policymakers focus on fostering genuine emissions reductions and credible disclosure practices, rather than viewing transparency as a shortcut to superior returns.

Several limitations should be acknowledged, including the specific European focus, the limited size of the transparent sample, and persistent measurement challenges around Scope 3 and other indirect emissions. As the CSRD becomes fully operational and sustainability standards continue to mature, future research will be needed to determine whether strengthened disclosure regimes lead to new pricing differentials or whether markets remain efficient in absorbing even the most granular climate-related information.

This article highlights the critical—yet bounded—role of carbon transparency in shaping long-term portfolio outcomes. The European experience suggests that market efficiency, regulatory harmonization, and rising investor sophistication are converging to ensure that transition risk is increasingly priced. However, the search for systematic green alpha may remain elusive in the absence of genuine information shocks or structural market changes. Going forward, sustained improvements in disclosure quality, will be essential for both financial and environmental progress.

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Appendix: Variables Definitions

Below is a concise overview of the variables used in our cross-sectional regression models, with definitions, interpretations, and data sources. Carbon and policy variables are from Eurofidai (ESG), while financial and sector data come from LSEG Workspace. Abnormal returns (α_i) are computed with Fama-French European factors from the Kenneth R. French Data Library.

Variable	Definition	Purpose	Data Source
Dependent variable			
α_i	Fama-French alpha over a 9-year period, estimated as the intercept of the five-factor model: excess return unexplained by market, size, value, profitability, and investment factors.	Captures long-term risk-adjusted performance at the firm level.	Kenneth R. French (European factors), LSEG returns.
Emission variables			
CarbonGap	Year-over-year change in total emissions $\frac{EMCO2_t - EMCO2_{t-1}}{ EMCO2_{t-1} }$.	Captures transition progress or setback; positive if emissions rise, negative if they fall.	Eurofidai ESG, author's calculation.
logScope1	Natural logarithm of Scope 1 emissions (direct GHG).	Direct operational carbon footprint, reflects on-site production/combustion.	Eurofidai ESG.
logScope2	Natural logarithm of Scope 2 emissions (indirect, purchased energy).	Captures emissions from purchased electricity, heating/cooling.	Eurofidai ESG.
logScope3	Natural logarithm of Scope 3 emissions (value chain).	Emissions from supply chain, upstream and downstream activities.	Eurofidai ESG.

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Variable	Definition	Purpose	Data Source
Other Pollutants	Natural log of total NOx, SOx, and VOC emissions.	Measures non-carbon pollutants, capturing broader environmental impact.	Eurofidai ESG.
POLENV	Score from 0–6 indicating the breadth of disclosed environmental policy: climate change risks, environmental investments, SOx and NOx reduction policy, Emission reduction policy, Emission reduction target, VOC reduction policy..	A proxy for the firm’s environmental strategy and governance. Higher scores reflect more rigorous policy.	Eurofidai (ESG dataset), author’s scoring.
ICB	Dummy variables for firm’s sector (Industry Classification Benchmark).	Controls for industry-specific effects in emissions and returns.	LSEG (ICB sector codes).
Controls			
LogSize	Natural logarithm of market capitalization (log(Market Cap)), in EUR.	Controls for firm size, affecting risk, access to capital, and returns.	LSEG Workspace.
LEV (Leverage)	Financial leverage: $\frac{\text{Total Debt}}{\text{Total Assets}}$.	Assesses proportion of firm’s assets financed by debt; financial risk.	LSEG financials.
OpMrg (Operating Margin)	Ratio: $\frac{\text{Operating Profit}}{\text{Total Revenue}} \times 100$	Measures core profitability and operational efficiency.	LSEG financials.
B/M (Book-to-Market)	Book value per share divided by market price per share.	Valuation metric, used to identify value/growth firms.	LSEG, author’s calc.

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Variable	Definition	Purpose	Data Source
ROE	Return on Equity: $\frac{\text{Net Income}}{\text{Shareholders' Equity}} \times 100$	Profitability relative to equity base; used to assess management performance.	LSEG financials.
ε	Error term, robust and clustered at the firm level.	Captures all unobserved effects in the regression.	Statistical model.

Table 1: Summary Statistics

This table reports summary statistics for the variables used in our main regressions. All values are based on a sample of 315 firms over 9 years. Following Bolton & Kacperczyk (2021), we apply the winsorization method to different variables at different values; the percentage is determined according to Aswani et al., 2024. Variable definitions are provided in Appendix 1.

Variable	Winsorization [Cutoff(%)]	Mean	Std.dev	Median
Dependent variables				
Alpha Fama-French	–	-0.156	0.005	-0.157
Emissions variables				
CarbonGap	–	0.160	2.621	0.002
logScope1	–	10.244	3.277	10.087
logScope2	–	9.798	2.848	9.946
logScope3	–	13.187	3.112	13.362
logOtherPolluants	–	4.841	3.337	5.014
POLENV	–	1.446	1.655	1.000
Controls				
LogSize	–	8.016	2.253	8.423
Leverage	2.5	21.522	13.327	21.275
OpMargin	–	-0.580	311.340	11.670
B/M	2.5	0.687	0.625	0.511
ROE	2.5	10.787	65.538	11.420

Table 2: Sector-Neutral Quintile Portfolios

This table presents annualized risk-adjusted performance and mean returns for five sector-neutral portfolios sorted by carbon intensity, rebalanced annually from 2016 to 2024 ($N = 108$ months per portfolio). Portfolios are formed within sectors, from Q1 (lowest carbon intensity, "Green Leaders") to Q5 (highest, "Brown Laggards"). Alpha is estimated using the Fama-French five-factor model. The t-statistics test the null hypothesis that the mean equals zero. Symbols *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Portfolio	Alpha (Ann.)	t-stat	N	Mean Return (Ann.)	t-stat
Q1 – Low-carbon (Green Leaders)	-1.80	-9.70***	108	0.0951	6.50***
Q2 – Low-Mid	-1.87	-10.25***	108	0.0219	2.58**
Q3 – Mid	-1.89	-10.28***	108	0.0062	0.69
Q4 – High-Mid	-1.90	-10.35***	108	-0.0033	-0.34
Q5 – High-carbon (Brown Laggards)	-1.90	-10.41***	108	-0.0080	-0.85

Table 3: Bi-Dimensional Sort Portfolios

This table shows annualized Fama-French alphas and mean returns for portfolios double-sorted each year on both carbon intensity quintiles (Q1–Q5) and emissions trajectory ("Gap": Low, Mid, High), rebalanced from 2017 to 2024 ($N = 96$ months per portfolio). Alphas are from the Fama-French five-factor model. t -statistics test the null hypothesis that the mean equals zero. Significance: *, **, and *** at the 10%, 5%, and 1% levels, respectively.

Portfolio	Alpha (Ann.)	t -stat	N	Mean Return (Ann.)	t -stat Mean
Q1 – LowGap	-2.00	-10.06***	96	0.1020	3.99***
Q1 – MidGap	-2.04	-10.11***	96	0.0702	3.34***
Q1 – HighGap	-2.02	-10.02***	96	0.0837	4.39***
Q2 – LowGap	-2.10	-10.63***	96	0.0010	0.09
Q2 – MidGap	-2.10	-10.58***	96	0.0032	0.31
Q2 – HighGap	-2.05	-10.37***	96	0.0611	3.89***
Q3 – LowGap	-2.11	-10.67***	96	-0.0076	-0.68
Q3 – MidGap	-2.11	-10.60***	96	-0.0021	-0.21
Q3 – HighGap	-2.08	-10.41***	96	0.0207	1.85*
Q4 – LowGap	-2.12	-10.75***	96	-0.0132	-1.16
Q4 – MidGap	-2.11	-10.57***	96	-0.0009	-0.08
Q4 – HighGap	-2.11	-10.63***	96	-0.0069	-0.67
Q5 – LowGap	-2.12	-10.77***	96	-0.0166	-1.48
Q5 – MidGap	-2.11	-10.71***	96	-0.0053	-0.55
Q5 – HighGap	-2.11	-10.69***	96	-0.0097	-0.96

Table 4: Environmental Policy Tilt Portfolios

This table reports annualized Fama-French alphas and mean returns for sector-neutral portfolios tilted towards higher environmental policy disclosure (POLENV score ≥ 3), rebalanced annually from 2016 to 2024 ($N = 108$ months per portfolio). Alphas are from the Fama-French five-factor model. t -statistics test the null hypothesis that the mean equals zero. Significance: *, **, and *** at the 10%, 5%, and 1% levels, respectively.

Portfolio	Alpha (Ann.)	t -stat	N	Mean Return (Ann.)	t -stat Mean
Q1 – Tilted	-1.80	-9.74***	108	0.0879	6.02***
Q2 – Tilted	-1.88	-10.27***	108	0.0147	1.73*
Q3 – Tilted	-1.89	-10.30***	108	0.0043	0.48
Q4 – Tilted	-1.90	-10.35***	108	-0.0040	-0.41
Q5 – Tilted	-1.90	-10.40***	108	-0.0065	-0.69

Table 5: Long–Short Strategy — Sector-Neutral Quintile Portfolios

This table reports annualized alpha differences between sector-neutral quintile portfolios (long minus short) based on carbon intensity. “Q1” represents Green Leaders (lowest carbon), “Q5” Brown Laggards (highest carbon). All alphas are estimated via the Fama-French five-factor model over 2016–2024. Positive differences indicate higher risk-adjusted returns for greener portfolios.

Long Portfolio	Short Portfolio	Alpha Difference
Q1 – Low-carbon (Green Leaders)	Q2 – Low-Mid	0.0752
Q1 – Low-carbon (Green Leaders)	Q3 – Mid	0.0898
Q1 – Low-carbon (Green Leaders)	Q4 – High-Mid	0.0993
Q1 – Low-carbon (Green Leaders)	Q5 – High-carbon (Brown Laggards)	0.1038
Q2 – Low-Mid	Q3 – Mid	0.0146
Q2 – Low-Mid	Q4 – High-Mid	0.0241
Q2 – Low-Mid	Q5 – High-carbon (Brown Laggards)	0.0286
Q3 – Mid	Q4 – High-Mid	0.0095
Q3 – Mid	Q5 – High-carbon (Brown Laggards)	0.0141
Q4 – High-Mid	Q5 – High-carbon (Brown Laggards)	0.0045

Table 6: Long–Short Strategy — Bi-Dimensional Sorting

Annualized alpha differences for selected long–short portfolios formed by double sorting on carbon intensity (Q1–Q5) and emissions trajectory (LowGap, MidGap, HighGap). Positive values show the extent to which “cleaner” or “decarbonizing” portfolios outperformed. Table shows the highest, lowest, and representative intermediate spreads.

Long Portfolio	Short Portfolio	Alpha Difference
Q1 – LowGap	Q5 – LowGap	0.1168
Q1 – LowGap	Q5 – HighGap	0.1102
Q1 – LowGap	Q4 – LowGap	0.1114
Q1 – LowGap	Q3 – LowGap	0.1090
Q1 – MidGap	Q5 – MidGap	0.0732
Q1 – HighGap	Q5 – HighGap	0.0964
Q2 – HighGap	Q5 – HighGap	0.0658
Q1 – LowGap	Q2 – LowGap	0.0989
Q1 – MidGap	Q4 – HighGap	0.0743
Q3 – HighGap	Q5 – HighGap	0.0322
Q2 – LowGap	Q2 – HighGap	-0.0545
Q3 – LowGap	Q4 – HighGap	-0.0027
Q4 – LowGap	Q5 – LowGap	0.0054
Q4 – HighGap	Q5 – HighGap	0.0038

Table 7: Long–Short Strategy — Environmental Policy Tilt

Annualized alpha differences between portfolios tilted towards higher environmental policy scores (POLENV) in long–short constructions. “Q1 – Tilted” is most proactive on disclosure, “Q5 – Tilted” least. Positive alpha differences reflect outperformance by more transparent firms.

Long Portfolio	Short Portfolio	Alpha Difference
Q1 – Tilted	Q2 – Tilted	0.0749
Q1 – Tilted	Q3 – Tilted	0.0847
Q1 – Tilted	Q4 – Tilted	0.0930
Q1 – Tilted	Q5 – Tilted	0.0954
Q2 – Tilted	Q3 – Tilted	0.0099
Q2 – Tilted	Q4 – Tilted	0.0181
Q2 – Tilted	Q5 – Tilted	0.0206
Q3 – Tilted	Q4 – Tilted	0.0083
Q3 – Tilted	Q5 – Tilted	0.0107
Q4 – Tilted	Q5 – Tilted	0.0024

Table 8: Cross-Section Analysis – Alpha

This table reports cross-sectional OLS regressions (HC3 robust standard errors) where the dependent variable is the 9-year Fama–French alpha (*Alpha Fama-French*) computed over 2016–2024. Columns (I) and (II) use the full set of controls, while columns (III) and (IV) report “CarbonOnly” specifications including only emissions and policy variables. Country and Industry (ICB) fixed effects are included as indicated. All continuous variables are standardized prior to estimation. Standard errors are shown in parentheses. Symbols *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

	(I)	(II)	(III)	(IV)
CarbonGap	-0.0016979 (0.0019657)	-0.0008894 (0.0019399)	-0.0011143 (0.0020253)	-0.0003921 (0.0018987)
logScope1	0.0040045 (0.0061529)	0.0024996 (0.0062102)	0.0074223 (0.0060658)	0.0027139 (0.0061617)
logScope2	-0.0024321 (0.0034116)	-0.0028010 (0.0036412)	-0.0088351** (0.0038025)	-0.0066112* (0.0037609)
logScope3	-0.0033053 (0.0031535)	-0.0044312 (0.0046104)	-0.0096670*** (0.0035284)	-0.0087412** (0.0041975)
logOtherPolluants	-0.0040042 (0.0058721)	-0.0068546 (0.0053668)	-0.0051358 (0.0055622)	-0.0088225 (0.0053932)
POLENV	-0.0042636 (0.0047550)	0.0018583 (0.0051896)	-0.0137522** (0.0067367)	0.0023598 (0.0049395)
LogSize	-0.0211908*** (0.0052064)	-0.0143657** (0.0062463)	–	–
Leverage	-0.0011722 (0.0023978)	0.0002026 (0.0024693)	–	–
OpMargin	0.0001418 (0.0025908)	0.0016248 (0.0022491)	–	–
B/M	-0.0081009** (0.0039481)	-0.0031284 (0.0079654)	–	–
ROE	-0.0067435 (0.0041959)	-0.0071938** (0.0034677)	–	–
Country	No	Yes	No	Yes
Industry	No	Yes	No	Yes
Observations	273	273	273	273
R^2	0.278	0.368	0.204	0.344
Adj. R^2	0.248	0.246	0.186	0.234

Figure 1: Autocorrelation Matrix

This table displays the lower-triangular Pearson correlation coefficients among the key variables: carbon emissions, environmental disclosure, financial controls, and risk-adjusted performance. Refer to the Appendix for precise variable definitions. All variables are winsorized at relevant cutoffs.

	CarbonGap	logScope1	logScope2	logScope3	logOtherPolluants	POLENV	LogSize	Leverage	OpMargin	B/M	ROE	Alpha Fama-French
CarbonGap	1											
logScope1	0.022	1										
logScope2	0.027	0.770	1									
logScope3	0.017	0.721	0.653	1								
logOtherPolluants	0.019	0.838	0.656	0.709	1							
POLENV	-0.045	0.128	0.092	0.150	0.112	1						
LogSize	-0.001	0.515	0.541	0.595	0.474	0.243	1					
Leverage	0.023	0.080	0.080	0.024	0.041	0.036	0.060	1				
OpMargin	-0.002	0.096	0.121	0.134	0.123	-0.017	0.050	-0.097	1			
B/M	-0.008	-0.016	-0.031	-0.051	0.002	0.016	-0.287	-0.081	0.043	1		
ROE	-0.001	0.003	0.043	0.039	0.023	0.021	0.090	0.019	0.075	-0.079	1	
Alpha Fama-French	-0.004	-0.288	-0.321	-0.343	-0.296	-0.125	-0.487	-0.058	-0.072	0.031	-0.044	1

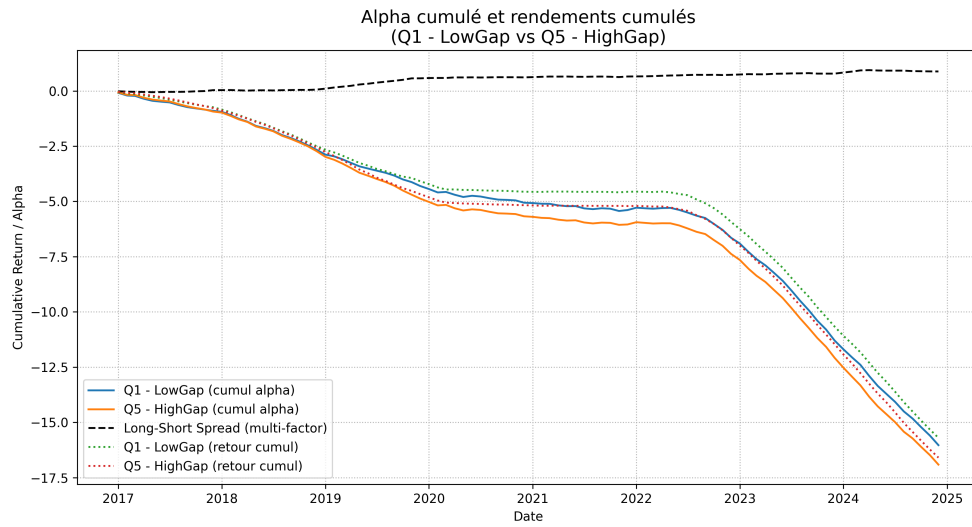


Figure 2: Cumulative Alpha for Q1 (Green Leaders) Long-Short Portfolio.

This figure illustrates the cumulative Fama-French alpha for the long-short portfolio based on Q1 (Low-carbon “Green Leaders”) versus Q5 (High-carbon “Brown Laggards”). Returns are annualized and factor-adjusted. See Table 2 for the associated summary statistics.

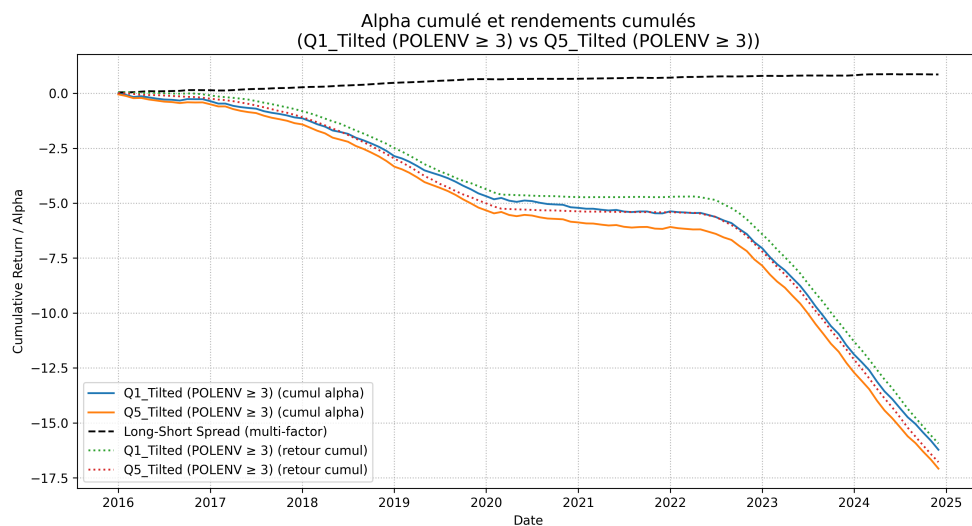


Figure 3: Cumulative Alpha for POLENV-tilted Portfolio.

This figure shows the evolution of cumulative risk-adjusted returns (Fama-French alpha) for the long-short portfolio tilted towards firms with above-median environmental policy disclosure (POLENV ≥ 3). See Table 4 for details and summary statistics.