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Reassessing Environmental Performance Within ESG Frameworks: Efficiency-Based Evidence From Multinational Firms

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ABSTRACT

The paper explores the evolving relationship between decarbonization strategies, environmental performance within ESG frameworks, and the economic performance of multinational companies in the context of increasing environmental and geopolitical uncertainty. Since the early 2000s, there has been a growing convergence towards greener and more sustainable business models, including the sectors of finance and banking. However, the recent technological transformation and geopolitical tensions pose challenges to the green transition, affecting its economic feasibility and environmental effectiveness. We adopt a risk-management perspective and argue that aggregate ESG scores may obscure the financial implications of environmental behavior. Using a multi-stage modeling approach—combining a preliminary dynamic framework with principal component analysis and efficiency benchmarking (DEA)—we test whether improvements in environmental performance translate into improved revenue growth in 16 multinational firms (2015–2023). Results show that even cost-free emissions reductions do not guarantee better economic outcomes, challenging the assumption that E[SG] improvements are necessarily growth-enhancing. Across differential-equations modeling, PCA regressions, DEA benchmarking, and simulated "cost-free" environmental improvements (up to 20%), we do not find evidence that environmental improvements per se raise revenue growth.

1 | Introduction

The financial transition towards sustainability has become increasingly intertwined with systemic risk dynamics. As capital markets internalize environmental externalities, ESG finance is no longer confined to ethical investment but has evolved into a mechanism affecting corporate resilience and financial stability. Within this broad ESG architecture, however, the environmental pillar represents the most measurable and operationally comparable dimension, grounded in physically quantifiable indicators such as emissions, energy use, water consumption, and waste generation.

Green and sustainability are increasingly present in many facets of the modern economy. Across sectors and countries, since the early 2000s there is a global dynamic of convergence towards providing greener and more sustainable products and services. Finance and banking have not been immune from this global trend: not only the financial intermediaries and commercial banks have been increasingly embedding green and sustainability in their provision, but also the regulators are increasingly paying attention to green and sustainability at systemic level for financial intermediation.

This growing convergence is progressively transforming sustainability from a voluntary corporate commitment into a measurable dimension of financial and strategic performance. Yet, the global diffusion of ESG frameworks has occurred unevenly across industries and jurisdictions, reflecting both institutional pressures and market incentives. Such heterogeneity creates

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uncertainty in assessing how multinational firms adapt their business models and governance practices to the new sustainability paradigm.

The global transition towards sustainability and ESG (environmental, social, and governance) principles has gained significant momentum over the past two decades. This paper examines how multinational companies navigate this transformation while facing geopolitical challenges, technological advancements, and regulatory pressures. However, given the structural heterogeneity of ESG dimensions, the empirical analysis concentrates on the environmental pillar, where disclosure is more grounded in measurable physical indicators and less dependent on qualitative assessment.

While much of the existing literature focuses on ESG disclosure or how ESG relates to performance at portfolio-level, few models attempt to simulate the dynamic impact of environmental decisions on firm-level financial performance under uncertainty. This paper addresses that gap. We adopt a multi-stage modeling approach; in fact, starting from differential equations and evolving into an empirical framework based on principal components analysis and scenario simulations.

After a paragraph taking stock of the literature about latest developments in the field, we comment on a few crucial issues currently gaining the attention of observers, or whose relevance can hardly be evaluated, like the consequences of new geopolitical scenarios, and the role of AI as a driver or inhibitor for decarbonization.

More specifically, the key challenges in ESG implementation are discussed, with a focus on emerging issues, including the limitations of current ESG metrics, corporate social responsibility dilemmas, and the influence of AI and digitalization on sustainability.

Then the geopolitical and economic pressures are explored: how defense spending, economic crises, and regional instability affect global sustainability commitments.

The final part of the work consists in the empirical section, where the authors try to unveil the benefits stemming from ESG strategies and to evaluate the impact of ESG variables on revenues. A data-driven assessment of these firms, modeling their resilience and financial performance in relation to sustainability, is also part of the analysis.

This paper investigates whether improvements in environmental performance—measured through emissions, energy, water, and waste—translate into superior revenue growth for multinational firms, under different geopolitical and technological constraints, rather than relying on aggregated ESG scores that may embed heterogeneous effects. By integrating theoretical insights with empirical testing, we examine whether improvements in environmental performance—measured via emissions, energy, water, and waste—systematically translate into stronger revenue growth. Contrary to widespread expectations, our findings suggest that environmental efficiency improvements do not automatically generate superior economic outcomes, calling for a more cautious interpretation of sustainability–performance linkages.

2 | Literature Review

The literature around the issues discussed in this paper is evolving rapidly, both the background topics—that is, how sustainability strategies evolve in a context of economic-technological and geopolitical challenges—and the relationship between AI and ESG, the forthcoming new political order, as well as transition and transparency (or disclosure).

The role of artificial intelligence in all issues somehow related to ESG is now widely debated. AI is gaining relevance for areas such as resources allocation, environment monitoring, strategies to improve business practices, and—from our own perspective—even as a tool possibly crucial to unveil a lack of disclosure or information asymmetries. But this tentative landscape is not exhaustive of course. As far as the role of AI in ESG investing, for instance, Zhang and Yang (2024) discuss how AI adoption improves environmental and social dimensions but has limited effects on governance structures. Wang et al. (2024) find that AI-powered manufacturing systems reduce carbon emissions, particularly in energy-intensive sectors. Sætra (2022) introduces an AI ESG protocol to standardize sustainability assessments, aiming to improve ESG reporting accuracy. Zechiel et al. (2024) further explore how major tech firms (Amazon, Google, IBM, Meta, Microsoft, SAP) leverage AI to optimize their ESG strategies, raising concerns about AI biases in sustainability assessments.

Geopolitical uncertainties, on the other hand, pose risks to ESG adoption and sustainability transitions. Kovacs et al. (2024) argue that during geopolitical crises, investors prioritize governance over environmental and social factors.

Transparency in ESG reporting is a widely recognized challenge. Both Tamimi and Sebastianelli (2017), and Pompella and Costantino (2023) observe that governance (G) factors tend to have the highest disclosure levels, while environmental (E) factors remain the least transparent. Yu Pei-yi and Van Luu (2021) find that firm-specific characteristics influence ESG disclosure volatility more than country-specific regulations. McBrayer (2018) highlights that firms with longer management tenure exhibit lower variability in ESG disclosures. Eng et al. (2022) show a positive correlation between ESG scores and market valuation, reinforcing the financial benefits of improved ESG transparency.

Several studies explore the financial implications of transitioning to ESG-focused business models. Raghunandan and Rajgopal (2022), on the other hand, question whether ESG-labeled funds genuinely prioritize stakeholder interests or simply repackage conventional portfolios.

Krueger et al. (2020) show that climate risks have become central in institutional investment decisions, especially for long-term value preservation.

Concerns regarding the reliability of ESG ratings have also been raised. Amel-Zadeh and Serafeim (2018) emphasize that concerning ESG disclosure the most important impediment to the use of ESG information is the lack of reporting standards, while Chatterji et al. (2016) report a lack of convergence among methodologies, highlighting the difficulty of establishing objective ESG scores. Berg et al. (2022) document significant divergence in ESG ratings, questioning their reliability for comparative assessments. Sætra (2022) warns that AI-driven ESG assessments may introduce systematic biases. Jiao et al. (2024) find that AI improves corporate environmental management but does not necessarily enhance governance structures. Tian et al. (2024) argue that digital transformation enables more accurate ESG reporting but also creates data reliability challenges. Pompella and Costantino (2023) propose a disclosure-adjusted ESG metric (*DAdj index*) to address asymmetric information, advocating for more responsible investment practices.

3 | Research Hypotheses

The existing literature above mentioned has extensively examined ESG ratings, disclosure practices, and investor reactions, highlighting substantial divergences across rating providers and measurement approaches (Berg et al. 2022; Chatterji et al. 2016). Evidence also shows that investors incorporate climate and sustainability risks into decision-making processes (Krueger et al. 2020; Amel-Zadeh and Serafeim 2018), while market reactions to ESG-related shocks may differ across environmental, social, and governance pillars (Kovacs et al. 2024). At the same time, concerns remain regarding the alignment between ESG ratings, disclosure practices, and actual stakeholder outcomes (Raghunandan and Rajgopal 2022). These findings suggest that the sustainability–performance relationship is mediated by measurement choices, rating divergence, and contextual factors rather than representing a mechanically positive association.

In light of the debate on whether sustainability investments systematically enhance performance, and building on the preceding discussion, the analysis concentrates on the relationship between environmental performance and firm-level revenue dynamics. We formulate the following hypotheses therefore:

H1. *Improvements in environmental performance are positively associated with revenue growth in multinational firms.*

H2. *Environmental efficiency indicators provide more stable explanatory power for revenue dynamics than aggregated sustainability ratings.*

In addition to these testable hypotheses, the analysis is situated within a broader technological and geopolitical transition context. In globally exposed and energy-intensive sectors such as automotive and technology manufacturing and service, environmental performance may be influenced by structural forces—including digital transformation, artificial intelligence diffusion, energy price volatility, and geopolitical instability—that shape compliance costs and transition risk. While these factors are not directly parameterized in the empirical model, they provide an essential boundary condition for interpreting the sustainability–performance nexus examined in this study.

4 | ESG at a Turn Point

4.1 | ESG in the Current World: Are New Geopolitical Scenarios and Technology Advancements Decelerating the Green Transition?

The green transition accelerated in the last few years thanks to the reinforced narrative and enhanced scientific underpinnings about climate change: there is consensus that a greener and more sustainable planet requires new approaches to the way we produce and consume. Initial awareness and consensus about climate change are now evolving with different attitudes and approaches towards the green transition depending on geography, levels of socio-economic development, and policy options and strategies adopted by different countries.[1]

The awareness among policy makers that actions are required is now consolidated; users and consumers gradually are embracing the green transition by adjusting consumption behaviors; industry and businesses are also transforming their processes for greener products and services. Yet, the geographical, social and economic unbalances among countries trigger questions at policy and practice levels on how to accelerate the green transition by bridging the gaps between strategies, policies and enforcement: parameters and targets should be less ambitious? The set of incentives (not just financial ones) could be revisited? Should regulations be stronger in imposing green transition targets with global coordination?

4.2 | Artificial Intelligence as a Driver for Decarbonization?

Technology advancements represent another critical juncture in the process of green transition. The advent of artificial intelligence (AI) will inevitably affect the finance and banking industry, to the point that AI is naturally embedded in the concept of FinTech. In the context of ESG finance, it is still too early to tell whether AI will be a driver or inhibitor in the process towards green transition and decarbonization. Pervasiveness of AI and its ethical challenges were already explored in Borenstein and Howard (2024).

AI enhances ESG indirectly by strengthening a firm's absorptive capabilities, and the effects vary across industries, with non-polluting sectors benefiting the most (Zhang and Yang 2024). AI adoption significantly enhances environmental efficiencies and performance by optimizing resource allocation, improving environmental monitoring, and fostering sustainable business practices. Wang et al. (2024) show that AI-powered manufacturing systems reduce carbon emissions, particularly in energy-intensive sectors. Their findings align with Sætra (2022), who proposes an AI ESG protocol to standardize the evaluation of AI's sustainability impacts.

The intersection of AI and sustainability is further explored by Zechiel et al. (2024), who analyze how leading tech firms (Amazon, Google, IBM, Meta, Microsoft, SAP), a few of them also included in our empirical analysis, leverage AI to enhance their ESG strategies. Their research underscores AI's potential in optimizing corporate sustainability efforts but also raises concerns about ethical AI use and bias in AI-driven ESG assessments.

AI technology and applications lend themselves to advancing the green transition by facilitating the technology behind decarbonization, the swifter and more accurate development of models for climate change mitigation and adaptation, as well as accelerating the design processes for new green technologies; and speeding industrial and manufacturing processes across industries and sectors.

Nonetheless, at the current stage of development, a few features emerge that may question the assumption that AI will provide only for positive contributions to green transition and ESG finance:

- The issue of energy intensity for large language models and AI applications raises the concern of the green coefficient of AI that may become a highly polluting factor of production.
- The efficiency gains introduced by AI in manufacturing may produce adverse environmental impacts if the increased production supported by AI is not more "energy efficient". In such instance, AI may lead to higher levels of production that by definition deteriorate the environment.
- As AI promises to "accelerate everything," the question remains on whether AI will also accelerate the human impact on the environment, hence AI as a driver for further anthropization.
- AI can also trigger new dynamics of "technology divide" that may only exacerbate the gap between countries and economies at different stages along the trajectory of the green transition.

Considering the above, the question on whether AI is a net-polluter or a net contributor to the green transition remains open. Time will tell if advancements in technology and green-tech will allow us to make AI carbon neutral.

4.3 | The Effectiveness of the Management Process and Monitoring

The varying intensity of implementation of the green transition should trigger global fora (i.e., COP29) to institutionalize the feedback loop and harmonize—or at the very least, coordinate—the commitments of specific countries and actors (such as the decarbonization commitment of the European Union to be climate-neutral by 2050 with the Green Deal and the commitment to become carbon neutral by 2030 of Microsoft Corporation[2]).

In the context of ever-changing and fast-evolving geopolitical settings and increased global business competitive pressures, the green transition might become burdensome for the "champions" that committed to long-term targets. A European Union engaged in various geopolitical fronts (conflict on the Eastern front with the war in Ukraine as well as upheavals in the Middle East) might lose motivation and resources to pursue the Green Deal. In the mid-term, the advent of new energy-intense technologies, such as Artificial Intelligence and cloud applications, might undermine the feasibility of green practices for large commercial operators.

The impact of geopolitical events on ESG priorities is a crucial theme. Kovacs et al. (2024) investigate the stock market reaction to ESG factors following the Russian invasion of Ukraine. Their findings indicate that firms with strong governance structures experienced abnormal positive returns, whereas environmental and social factors had limited influence. This suggests that during geopolitical crises, investors prioritize governance over other ESG dimensions.

Leaving aside the policy implications and deplorable human toll of conflict, there is the considerable environmental effect of ongoing conflicts (the wars in Ukraine and the Middle East, just to mention the latest conflicts) that will affect the speed of the green transition. By the same token, the technological transformation triggered by the advent of Artificial Intelligence will require energy and resources (human and financial) at unprecedented levels, potentially slowing down the green transition.

4.4 | Transition and Corporate Social Responsibility

While technologies develop rapidly, the transition to ESG-focused business models presents both opportunities and challenges.

The finance and banking ecosystem is upgrading its role of intermediation in support of this "ESG transition," or transition to a sustainable economy,[3] developing new products (ESG investment) and processes (ESG ranking and rating). Moreover, the financial sector is proving instrumental to implement the green transition, providing investment and securing capital for green-tech and for the adoption of more sustainable and greener products and services.

Yet, concerns may arise on the realistic green and sustainability features of those investments. ESG ratings apply to business processes and not to products, paving the way for a possible paradox of ESG-virtuous companies that have sustainable processes to produce environmentally and/or socially questionable products and services. This paradox materializes in companies with good ESG ratings that produce socially questionable products, like potentially harmful products (alcohol, tobacco, weapons) or environmentally unsustainable ones (fossil fuels, chemicals, oil, etc.).

ESG is a trending phenomenon that is gaining traction with investors (retail and institutional), hence generating pressure for compliance—or at the very least, adherence—on the side of companies, particularly listed international companies.

The issue of "disclosure" still represents a weak link in the chain of the ESG domain. Any ESG rating, ranking, or assessment could not ignore or prescind from the level, depth, and rate of disclosure: the lower a company discloses, the higher the ESG rating could be.

In addition to potential failures of the ESG mechanism due to disclosure, some elements of the ESG may still appear counter-intuitive and raise questions about how a high-polluting company (i.e., an oil and gas corporation) could score highly in an ESG ranking. Merely as an example, in May 2022 Standards & Poor Global announced that Tesla, an electric vehicle company, would no longer be included in the S&P ESG Index due to unclear performance under the social pillar of ESG. Reportedly,[4] despite its commitment to greening the planet by promoting the adoption of electric vehicles, Tesla has had mixed results in the ranking due to working conditions in its US-based factory and overall *lack of a low-carbon strategy*.

There are inherent risks in those "disclosure mechanisms" with related doubt on the transparency of ESG compliance metrics and indicators, and the asymmetries behind inadequate practices. It has been observed how typically the best disclosure is related to Governance, while the lowest is associated with Environment and the footprint of companies' behavior (Tamimi and Sebastianelli 2017). Enhancing G-compliance (e.g., by increasing gender parity or opening the board of directors to under-represented groups) is easier and faster than working to reduce emissions.

On the other hand, most of the volatility in ESG disclosure depends on firm-specific characters (see Yu Pei-yi and Van Luu 2021), more than on country-specific factors. This is confirmed also when sectoral differentiation is considered. Another valuable example of how non-financial factors might alter disclosure is the relationship between the length of management's tenure and the reduced variability of disclosure (McBrayer 2018). Companies have a considerable degree of freedom in their disclosure, leading to low levels of transparency due to low levels of regulation. This leads to a strident comparison between "traditional financial reporting" and "ESG reporting": the former being highly regulated and "relevant, reliable, comparable" while the latter is in a relatively gray area.

From a different perspective, while a better quality of ESG reporting provides investors with a more accurate image of the company compliance and sustainability, ESG scores seem to be positively correlated with market value and prices (see Eng et al. 2022). Such correlation enhances the Economic, Environmental and Social (EES) sustainability performance, thanks to better governance (Alsayegh et al. 2020).

4.5 | Sustainability and Transition Costs

The new ESG related costs and risks will require companies, financial intermediaries, and regulators to identify innovative means for risk identification, management, and supervision. While the costs may be most probably passed onto consumers and investors, the financial and operational risks should find credible mechanisms that sustain the robustness of the economy.

Splitting the three domains could overcome any possible attempt at altering the final score by tinkering with the indicators and/or elements of the different dimensions. In fact, the building blocks of ESG can be differentiated depending on their inherent cost (of compliance and reporting) and potential impact (of image building and ranking).

The Governance domain might be relatively easy to implement and inexpensive to comply with, while generating high returns in terms of positive impact on the overall ESG rating and visibility for the company. Even merely cosmetic measures could enhance dramatically and almost instantly the G-indicator, with initiatives enforcing gender balance in top management or ensuring diversity in board membership. The Social dimension of the ESG could be described as medium cost to implement and comply with, but still associated with considerable "visibility" benefits and impact on the overall rating. It would suffice for a company to develop a work-life balance program or define an internal policy for diversity and inclusion to have considerable impact on the ESG rating. By the same token, launching a volunteering program within the community or financing other socially relevant activities might gain any company a good rating. The medium cost is identified in the need to build units to develop, manage and operate such programs.

The Environment building block of the ESG framework is probably the one that may represent a high cost for companies to implement, while generating uncertain impact on visibility and ESG rating. The high cost is associated with the costs directly related to compliance with environmental sustainability, from retrofitting production facilities and office space to "greening the value chain". Those interventions would entail considerable investments that would require time to yield benefits in terms of visibility and ranking.

Those features and differentiation between costs and impact of the three domains makes the overall ESG mechanism unbalanced and disproportionate. With relative ease, a company can increase its rating by appointing a representative of a minority to the board while continuing to pollute to produce weapons. Conversely, producing electric vehicles may provide a high score on the environmental dimension of ESG but should not discount the value of robust governance and social responsibility.

This structural asymmetry between the three pillars helps explain the analytical choice adopted in this study. While governance and social initiatives may influence ESG ratings—in some cases—with very limited operational transformation, environmental performance typically requires measurable, capital-intensive adjustments in production processes, energy use, and resource management. This is why the empirical analysis deals with the environmental dimension as the most comparable component within the ESG architecture. The transition towards environmental sustainability for any company entails significant overhauls of operational and risk management processes with substantial investments.

Naturally, this focus does not imply that the S and G dimensions are normatively secondary; rather, it reflects the view that environmental metrics provide the most robust basis for testing the sustainability–performance nexus under conditions of measurable transition costs.

5 | Transformation of Economies and Investors' Dilemma

5.1 | Green Attitude vs. Lack of Disclosure

The quest for green and sustainable is already producing considerable impact on the economy and the way we produce and consume. As mentioned, at present the economic actors are facing higher costs due to the infancy of the green revolution: while already underway, the green transition has yet to materialize the economies of scale of mature technologies and economic systems. The current green economy is far from having reached the maturity typical of economic cycles that have gone through the full stages of development.

The green transition and long-term objective of decarbonization might trigger new forms of "transition costs" and/or "ESG-related risks". The transition costs are represented by the investments and costs associated with the measures that economic agents and companies need to take to embed ESG practices. The "ESG-related risks" are all the business, financial and operational risks that companies might face due to increased environmental and social pressures emerging from a changing world. Environment-related costs and risks are inevitably associated with climate change, both mitigation and adaptation. Social costs and risks are linked to civic/social unrest that might affect labour relations, supply chains and demand for goods and services. Governance costs and risks may be associated with the cost of financing (i.e., would it be ESG-compliant for a start-up to accept funding from a Venture Capital fund associated with an unfriendly country) or operations.

While ESG and responsible finance were gaining traction with institutional as well as retail investors, the proliferation of rankings, ratings and indicators facilitated the awareness about and attention towards environmental, social and governance metrics used by investors to base their financial decision-making processes. Such growing interest from retail investors triggered the development of innovative financial products, like ESG Mutual Funds and ESG Exchange-Traded Funds (ETF) labeled with enticing names of the likes of "responsible," "sustainable advantage" and even financial products directly linked to the Sustainable Developmental Goals (SDG) of the United Nations.

Rankings, indicators and innovative financial products are giving ESG mass-market appeal: retail investors pay increasing attention to environmental, social and governance factors for portfolio construction and investment decisions.

Combining E + S + G may lead to a result that is partial and potentially smaller than the whole, ultimately with the adverse effect of misleading investors and users—especially the less sophisticated ones that might limit their analysis to the final score rather than delving into the score across dimensions, indicators, and sub-indicators.

5.2 | Disclosure, Transparency, and ESG Reliability

Transparency and standardization in ESG disclosures are critical in order to evaluate corporate sustainability performance. Sætra (2022) introduces a structured AI ESG protocol to improve ESG reporting standards, ensuring firms disclose reliable and verifiable sustainability data. Pompella and Costantino (2023), propose a new "disclosure adjusted" metric based on publicly available *GHG Scope-1* values, the *DAdj index*, with the purpose of reducing asymmetric information to the benefit of more responsible investment. Tian et al. (2024) highlight how digital transformation enhances ESG disclosures, enabling firms to leverage big data for more accurate sustainability reporting.

The current configuration of ESG models bundle and integrate three dimensions that are related to environmental and social sustainability and good governance. The ultimate goal of measuring how virtuous companies and businesses are deserves more thorough approaches. The ESG approach has gained so much traction and attention that time series of data and information are becoming available. The social and governance dimensions are also evolving to encompass new features and indicators; companies and analysts have access to more granular data for the environmental dimension; data processing techniques are improving and the amount of big-data has considerably increased in the recent past. Such evolutions and dynamics may pave the way for a revised approach towards measuring the sustainability of companies. Nevertheless, the increasing availability of data does not automatically settle the structural heterogeneity of the pillars. Environmental indicators are typically defined as physical and measurable quantities (emissions, energy use, resource consumption), whereas social and governance dimensions often rely on qualitative assessments, policy directives, or institutional codifications that can hardly be standardized across firms and jurisdictions. This asymmetry in measurability and comparability raises methodological challenges when aggregate ESG scores are used as explanatory variables in financial analysis. Bundling such heterogeneous dimensions might have been reasonable at the onset of the wave of the ESG trend, when the infancy of the "responsible" finance, investment and business needed to make way. Now that the ESG is rising to a core element of financial decision making and business approaches, the model deserves a restyling, also to counter the argument that ESG is "woke" and address the growing criticism of "woke capitalism" that is emerging in the USA where ESG is increasingly becoming a politically polarizing factor.

Precisely because ESG is not about political issues and beliefs but is a mechanism to introduce incentives to behave, increase transparency and maintain discipline in the market (at both business and finance levels), these three dimensions that are functionally distinct and unrelated deserve their own dignity and to stand on their own. Bundling three unconnected business features, functions and attitudes is no longer relevant:

The consolidation of these three dimensions does not do justice to none of the participants:

- Environmentally friendly companies might not shine in ESG rankings due to traditional human resource practices.

- Less-virtuous companies would be able to compensate for poor environmental performance with governance approaches or social initiatives that would boost their ESG rating.

- Investors can be misled by ratings based on aggregate results stemming from unrelated business dynamics and indicators.

Notwithstanding the merits of efforts to gauge the environmental (E), social (S), and governance (G) sustainability and responsibility of companies through the ESG model, there are features that might undermine its validity and call for evolutions and improvements of the ESG framework. First, there is the vexing issue of disclosure and reliability of the information provided by companies. ESG reporting is increasingly becoming mandatory in Western jurisdictions, with the most relevant novelty being the Corporate Sustainability Reporting Directive (CSRD) of the European Union that entered into force in late 2023. The CRSD mandates for European large and listed companies (as well as listed Small and Medium Enterprises) to report on sustainability. Some non-EU companies will also be required to report on ESG if they generate more than EUR 150 million in the European Single Market.

Effectively, the new EU legislation requires that all large and listed companies disclose information on "what they see as the risks and opportunities arising from social and environmental issues, and on the impact of their activities on people and the environment." The interpretation may remain vague and only time will tell on the effective impact of the new Directive on companies, investors and regulators as the gradual rollout started in 2025 (the first batch of companies will have to apply the new rules for the first time in the 2024 financial year, for reports published in 2025). Nonetheless, there is still considerable leeway for companies to identify the risk features and the potential impact on people and the environment.

Second, the ESG reporting has hitherto been on a voluntary basis practically, making it difficult to rely on the data currently available. The current knowledge and data base remain fragmented and patchy with uneven time series that do not allow for adequate analysis over time, undermining the identification and analysis of trends.

Third, in spite of efforts to harmonize the three dimensions of the ESG framework, the underlying nature and characteristics of the fields to be measured (environment, social and governance) as well as the heterogeneity of the indicators identified to gauge them may undermine the validity of the framework.

Finally, and most importantly, the structure and weighting of the ESG framework may provide room for a sort of "substitution effect". While ESG ratings and rankings provide for individual assessments along the three dimensions, the final score is still achieved by gathering an aggregate result along the three different areas. Hence a relatively poor performance in an area, that is, Environment, could be easily compensated by a better than average performance in another area, that is, Social. Such substitution effect may morph into artificial conduct of companies that might even devise compensation strategies taking into account cost and return for their performance across the three dimensions. While institutional investors might have the time, resources and capacity to delve into the data to make a more thorough assessment of the ESG performance of a given company, the retail and less careful investor might not have the patience—nor the information—to go more granularly through the underlying indicators and base their investment decisions on the aggregate ESG rating of a company.

5.3 | Strategic Rationale for ESG Investments

A final topic worth considering and which introduces the last section, that is the empirical part, is the relationship between investments in sustainability and the company's resilience, in the medium-long term.

This mainly relates to the market's perception of the company's efforts to make itself ESG compliant. The consideration that a company that protects itself from catastrophic risks is faced with a dilemma is coming from the theory of Pure Risk Management (PRM), as one of the foundations of PRM itself. And this dilemma consists of the following two options: either to manage the risk by making the firm less vulnerable, assuming that the cost of doing so (insurance, market, or whatever other contractual arrangement) is lower than the benefit it derives from it, or to adopt a passive strategy, remaining risk-prone.

In a competitive environment and assuming full transparency, or at least uniform information asymmetries (i.e., assuming that the level of disclosure does not depend on the company or the sector), we have to conclude that the company that invests in sustainability is better equipped to face the future, and less "at risk" in terms of compliance, but only if regulatory compliance is associated with a substantial benefit.

The following section therefore aims to ascertain whether a company that invests in ESG is likely to perform better, and thus create value for shareholders.

6 | The Empirical Analysis

6.1 | Introduction

Our empirical analysis follows a multi-stage path, gradually evolving from a theoretical to a data-driven framework.[5]

The empirical strategy is aligned with the hypotheses formulated above. First, we test whether improvements in environmental performance are associated with revenue growth (H1) through collinearity analysis and PCA-based regressions. Second, we evaluate whether environmental efficiency indicators provide more stable explanatory power than aggregated sustainability ratings (H2) using a Data Envelopment Analysis framework. The final refined model consolidates these findings and assesses their robustness under alternative specifications.

As a conceptual step, we start developing a system of differential equations to represent the potential co-evolution of firm revenues and sustainability-related variables. While theoretically informative, the empirical implementation of this dynamic model proved sensitive to data volatility and cross-firm heterogeneity. For this reason, it serves primarily as a theoretical foundation for the subsequent empirical refinements rather than as the core testing framework. To address data volatility and cross-firm heterogeneity, we then implemented PCA regression, aiming to reduce that volatility and reveal underlying connections between environmental performance indicators and revenue dynamics. PCA allows dimensionality reduction and the identification of latent environmental factors explaining the majority of cross-company variance. This technique is particularly suitable for sustainability data, where high inter-correlation among indicators may bias regression models.[6]

The subsequent DEA analysis was made to complement the new approach introducing a non-parametric perspective, and to assess relative efficiency.

The goal throughout was to evaluate, from complementary methodological perspectives, whether improvements in environmental performance and efficiency are systematically associated with firm-level revenue growth.

A way of testing the depth of the ESG models and ratings is to isolate specific indicators of the Environmental dimension for an empirical analysis of the behavior of companies. When isolated, the three indicators of total energy consumption, total water use, and total waste can provide a proxy to observe the reliance and resilience of the ESG model to gauge the behavior of companies.

In our case, we selected companies from different sectors and segments of the economy. Specifically, only those companies from those diverse sectors for which ESG data and rankings from the Bloomberg ESG were available for the timeseries between 2015 and 2023 (latest considered data). Here is the list of the companies in the sample (Table 1).

We have been working then to the hypothesis of modeling, through a differential equation model, and different subsequent approaches, the behavior of Revenues as a function of Energy Consumption, Water consumption, Waste production, also taking stock of Bloomberg index of sustainability. Every step was R software implemented.

A review of our work on modeling through a differential equations approach Revenues (R) as a function of GHG Scope 1 emissions, Energy Consumption (E), Water Consumption (W), and Waste Production (T), also taking stock of the Bloomberg ESG score (BESG), is given in the Appendix A (1st and the 2nd version). We provide the outline of the step-by-step evolution of our models, including all the hypotheses behind each version, the reasons for changes, and why we incorporated nonlinearity. We began with a system of first-order differential equations, in fact, to represent the co-evolution of firm revenues and environmental factors. However, these models proved difficult to estimate empirically: numerical derivatives were noisy, and identification was weak across firms.

To address the above issues, we move here to a reduced-form, trying an empirical approach based on principal component analysis (PCA), which allowed us to condense GHG, energy, water, and waste into orthogonal composite components.[7]

6.2 | Key Findings From Collinearity Analysis (Averaged Variables) and PCA Regression

This section directly addresses H1 by examining whether variations in environmental performance indicators are systematically associated with differences in revenue growth across firms. Predictably, from the correlation matrix we can see that some of the implied variables reveal collinearity, as shown in the two heatmaps below, respectively by yearly defined or by average values, over the time interval considered (2015–2023) (Pyton generated) (Figure 1 and Table 2).

This suggests:

i. High correlation between energy and GHG Scope 1 (0.89).
   – This confirms that energy consumption and pollution (GHG) are closely related, and that
   – Keeping both in a regression model could lead to collinearity issues.

ii. Water use is moderately correlated with GHG and energy (~0.75).
   – What suggests that companies with higher emissions and energy use also tend to consume more water?

iii. Revenues and waste show a negative correlation (−0.14).
   – This could indicate that higher revenues lead to better waste management practices.

iv. BESG environmental score has a weak or mixed relationship with other variables.
   – We observe weak correlation with Revenues (−0.03), reinforcing that the BESG Score is exogenous.
   – Negative correlation with Waste (−0.25), suggesting firms with higher sustainability scores may reduce waste.

TABLE 1 | The companies considered in the empirical analysis.

F US Equity	FORD
MBG GR Equity	MERCEDES
7203 JT Equity	TOYOTA
VOW GR Equity	VOLKSWAGEN
BMW GR Equity	BMW
JPM US Equity	JPMORGAN
GS US Equity	G SACHS
DBK GR Equity	DEUTSCHE BANK
CL US Equity	COLGATE-PALM
NESN SW Equity	NESTLE
KMB US Equity	KIMBERLY-CLARK
MSFT US Equity	MICROSOFT
INTC US Equity	INTEL
SAP GR Equity	SAP
GOOGL US Equity	ALPHABET
ANA SM Equity	ACCIONA

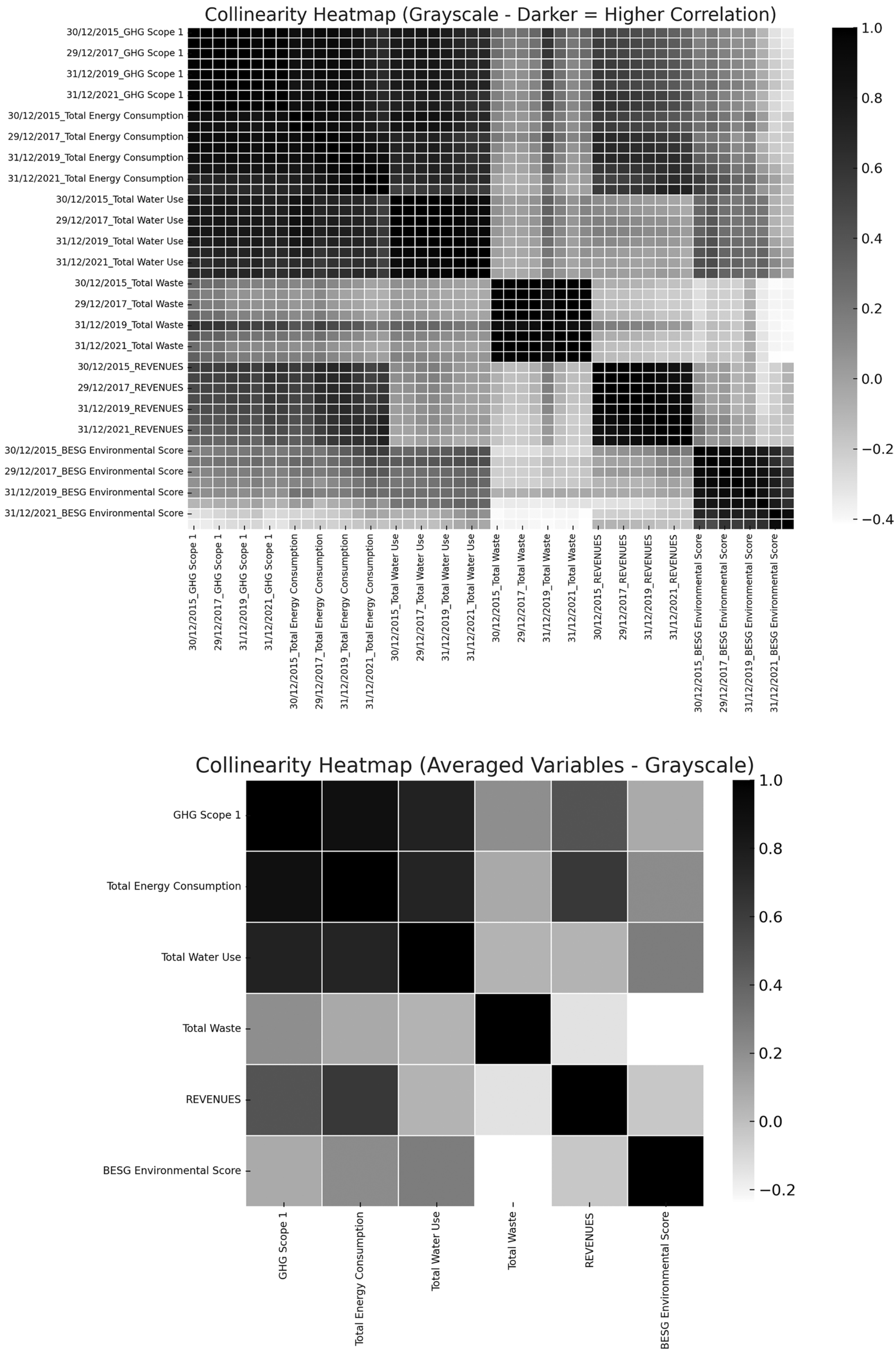

FIGURE 1 | Correlation heat maps (non-grouped vs. grouped).

TABLE 2 | The correlation matrix between considered variables.

	GHG	Energy	Water	Waste	Revenues	BESG Score
GHG Scope 1	1.00	0.89	0.76	0.20	0.48	0.08
Total energy consumption	0.89	1.00	0.74	0.09	0.63	0.21
Total water use	0.76	0.74	1.00	0.05	0.04	0.28
Total waste	0.20	0.09	0.05	1.00	−0.14	−0.25
Revenues	0.48	0.63	0.04	−0.14	1.00	−0.03
BESG environmental score	0.08	0.21	0.28	−0.25	−0.03	1.00

TABLE 3 | The loadings of first three PCs.

	PC1	PC2	PC3
GHG Scope 1	0.55	0.16	0.04
Total energy consumption	0.57	0.02	−0.08
Total water use	0.48	−0.09	0.43
Total waste	0.05	0.71	0.39
Revenues	0.33	0.02	−0.74
BESG environmental score	0.15	−0.68	0.33

Collinearity persuaded us to apply PCA, in order to reduce the number of implied variables. Here are the loadings (Table 3).

The first principal component (PC1) captures most of the variation across the ESG-GHG variables, but its interpretation seems to be ambiguous. It shows positive loadings on both GHG emissions and the BESG environmental score, in fact, meaning it does not represent a clean *polluting* or *sustainable* direction. Instead, it seems to reflect a general intensity profile: firms with high ESG exposure and high emissions. PC2 and PC3 isolate more specific patterns, such as waste or water use, but they explain less variance overall. In other words, while PCA helps to fix the multicollinearity issue, it also introduces interpretive challenges, especially when the components mix signals from different domains.

From a new (PCA-based) regression (OLS, Pyton), with each equation following the general form:

$$\frac{dY}{dt} = \beta_0 + \beta_1 PC_1 + \beta_2 PC_2 + \beta_3 PC_3 + \epsilon \tag{1}$$

(where Y is R, P, E, W, A) we get the following estimated coefficients.

Revenue growth equation:

$$\frac{dR}{dt} = -23.14 - 15.03\, PC_1 - 6.45\, PC_2 - 2.93\, PC_3 \tag{2}$$

Pollution dynamics (GHG Scope 1):

$$\frac{dP}{dt} = -23.14 - 15.03\, PC_1 - 6.45\, PC_2 \tag{3}$$

Energy consumption equation:

$$\frac{dE}{dt} = -23.14 - 15.03\, PC_1 \tag{4}$$

Waste production equation:

$$\frac{dW}{dt} = -23.14 - 15.03\, PC_1 \tag{5}$$

Water consumption equation:

$$\frac{dA}{dt} = -23.14 - 15.03\, PC_1 \tag{6}$$

Looking at the estimates, PC1 is the dominant driver across all dynamic equations, affecting revenue, pollution, energy, waste, and water. PC2 appears only in the revenue and pollution equations, suggesting its limited explanatory power for energy, waste, and water consumption dynamics. PC3 influences revenue only and is excluded from all other models.[8]

The estimated coefficients indicate that all principal components (PC1-2-3) are negatively associated with revenue growth. This implies that increases in the underlying signals (as captured by positive PC values) are linked to a decline in the growth rate of revenues. Conversely, negative PC scores—representing a misalignment with the average behavior (the benchmark in PCs space), away from the latent ESG/GHG structure under scrutiny—are associated with higher revenue growth in this model (Figure 2).[9]

Our aim, anyway, is to assess if and how ESG compliance may influence Revenues. In other words, to assess if companies investing in Sustainability will have a competitive advantage in the future. We modeled the relationship between environmental factors and revenue growth, but not ESG investments explicitly. Our PCA components capture sustainability indicators (GHG, Energy, Waste, BESG) but do not address our question.

Updating the model then by modifying the first equation as follows:

$$\frac{dR}{dt} = \beta_0 + \beta_1 PC_1 + \beta_2 PC_2 + \beta_3 PC_3 + \beta_4\, BESG\ Score + \epsilon \tag{7}$$

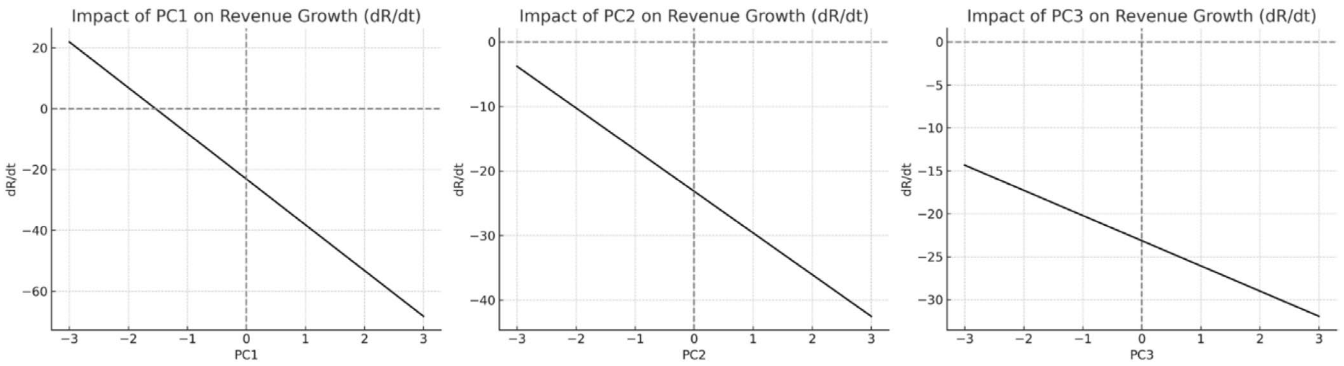

FIGURE 2 | PCs impact on revenues growth.

could not bring us to any conclusion, meaning that BESG score cannot improve the model, as it is statistically insignificant (see below). Also, BESG shows, as above mentioned, a positive loading as well, meaning that PC1 is not symptomatic of a polluting direction, like it would have been with all strongly positive loadings on (let's say) "polluting" variables and a strongly negative BESG loading.

In other words:

1. PC1 does explain most of the variance within the ESG/GHG structure (= it is the dominant driver).
2. A negative coefficient assigned to one of the PCs in the equation defined to evaluate the individual PCs' role means that, in terms of that specific PC involved, the firms are moving away from the "neutral" benchmark (the centroid, in the PCs space).
3. This would also mean that the common direction the firms move is a virtuous one, but only if we had strongly positive loadings on "polluting" variables and strongly negative BESG loading. Actually, we have a lower loading for BESG, but this is not enough to define "PC1 direction" as a polluting direction, and consequently the misalignment is like a plus.

We have reasons to suspect that the Bloomberg ESG Score (BESG), therefore, is not accurately reflecting any benefits deriving from firms' sustainability investments, or their relationship with revenue growth.[10]

Let's sum up the followed path till now: we started with a dynamic system of 5 differential equations to model co-evolution of revenue, emissions, and resource use. However, the empirical estimate of such a structure proved challenging, as derivative estimates were unstable, and equations beyond revenue growth were poorly identified.

To address this, we shifted to a regression based on PCs, focusing on revenue growth. This allowed us to reduce dimensionality, preserve the multivariate ESG/GHG structure, and test whether composite sustainability behavior explains differences in firm performance directly.

It is worthy to note the following. The PCA regression was statistically motivated by the high collinearity among original ESG/GHG variables. However, it must be acknowledged that the PCs do not clearly map onto a single environmental or sustainability axis. This is clearly shown by PC1, having positive loadings on both emissions and ESG scores, which makes its interpretation ambiguous.[11]

While PCA helps reduce noise and multicollinearity, it introduces trade-offs in terms of interpretability. Therefore, the regression results that follow should be read as indicative of statistical association rather than causal or conceptual clarity. This is precisely why we complement the analysis with DEA, below here, and a direct regression on raw variables, to triangulate the findings and expose inconsistencies that PCA alone may obscure.

6.3 | Data Envelopment Analysis (DEA)

Somehow ambiguous results from the previous section suggested us to approach the issue from a different perspective, and therefore to perform a DEA analysis, in order to test the efficiency over the period in the sample. The DEA analysis complements the regression results by addressing H2; in fact, evaluating whether environmental efficiency metrics provide a more consistent explanation of firm-level performance than aggregated sustainability ratings.

Below here the results, ordered by Multi-input DEA efficiency (the 7th column).

Interestingly, DEA scores do not align with the BESG ratings (also see Figure 3). Some companies with lower ESG scores achieve full efficiency, while others with high BESG ratings fall below the frontier. This reflects the fact that DEA evaluates technical efficiency in transforming inputs (like energy, waste, water, GHG) into outputs (revenues),[12] without assuming any normative ESG benchmark. The method is sector-neutral and purely data-driven, meaning that it rewards operational effectiveness rather than declared sustainability targets.

Table 4 presents the four efficiency scores by input (energy, water, GHG, waste), their average values, the multi-input efficiency score, considering all profiles at the same time, and the average value of BESG over the years in the sample. If a company shows a high BESG score, which reflects strong sustainability practices that should reduce costs and improve risk management, it would be reasonable to suppose this is reflected in its DEA efficiency. Even if BESG is peer based, and DEA does not pay here any attention to the specific sector.[13] The misalignment—here the ranking is not even comparable—is inspiring for further investigation.

The figure shows DEA surface (*inverse RBF smoothing*, *z* aspect ratio 0.3),[14] with bullet sizes proportional to average revenues (Figure 4).

6.4 | Final Refined Model

The above analysis, including the DEA check, suggests that PCA optimizes dimensions, but may obscure individual variable effects, and that the BESG score is statistically insignificant; on the other hand.

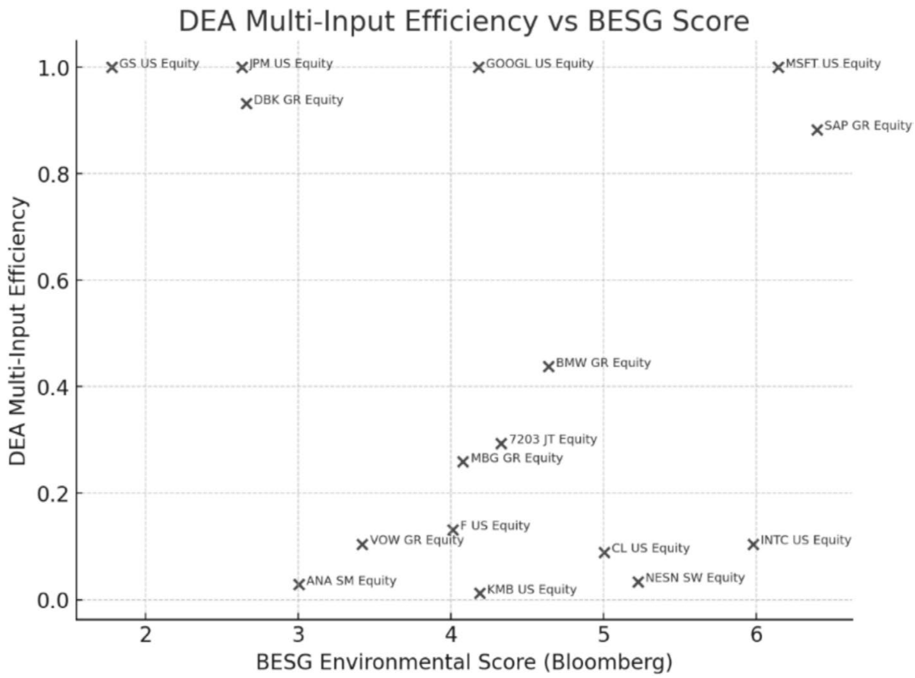

FIGURE 3 | DEA multi-input efficiency versus BESG environmental score.

TABLE 4 | Multi-input DEA analysis results.

	DEA efficiency scores						
Company	**Energy**	**Water**	**GHG**	**Waste**	**Avg_**	**Multi**	**BESG avg**
GOOGL US Equity	0.13	0.17	0.57	0.82	0.42	1.00	4.18
GS US Equity	1.00	1.00	1.00	0.47	0.87	1.00	1.78
JPM US Equity	0.51	0.36	0.35	0.85	0.52	1.00	2.63
MSFT US Equity	0.12	0.34	0.28	1.00	0.43	1.00	6.14
DBK GR Equity	0.57	0.57	0.21	0.53	0.47	0.93	2.66
SAP GR Equity	0.30	0.50	0.05	0.52	0.34	0.88	6.40
BMW GR Equity	0.19	0.44	0.04	0.03	0.18	0.44	4.64
7203 JT Equity	0.13	0.14	0.03	0.20	0.12	0.29	4.33
MBG GR Equity	0.17	0.26	0.06	0.03	0.13	0.26	4.08
F US Equity	0.11	0.13	0.03	0.03	0.07	0.13	4.01
INTC US Equity	0.08	0.02	0.01	0.06	0.04	0.10	5.98
VOW GR Equity	0.10	0.10	0.01	0.02	0.06	0.10	3.42
CL US Equity	0.09	0.03	0.02	0.02	0.04	0.09	5.01
ANA SM Equity	0.03	0.03	0.01	0.00	0.02	0.03	3.01
NESN SW Equity	0.03	0.01	0.01	0.01	0.02	0.03	5.23
KMB US Equity	0.01	0.00	0.00	0.00	0.01	0.01	4.19

We decided then to conclude our analysis by testing more explicitly our hypotheses about the relationship between being green and financial performance (the question is: does a virtuous ESG strategy improve performance?). Our analysis was performed therefore by building two extended datasets, to test two different scenarios: BAU (*Business As Usual*) and SIM (*Sustainability IMprovement*). Five years more were simulated:

1. In one case by leaving everything unchanged but maintaining historical trends for all variables.
2. In the second case instead, we imposed a progressive annual reduction (with no interpolation)[15] to the last observed values of GHG Scope 1 (emissions), Total energy consumption, total water use, total waste production, starting from 3%, until 20%.

This reduction was assumed to derive from Government incentives, meaning that is assumed to be obtained at no cost for companies. That is our model forced sustainability improvements without any financial burden on companies (i.e., as if a government subsidy, or in presence of any external intervention covering the costs). But even in this cost-free scenario no improvement in revenue growth was observed, even with aggressive ESG reductions (up to 20%). This suggests that if companies had to bear the costs themselves, their revenue growth could be worse, not better.

Based on these pre-emptive results, we could reasonably hypothesize that companies could have had slower revenue growth—or even revenue decline—if they implemented ESG strategies voluntarily and bore all associated costs.

The reasons for such an unforeseen result stem from the circumstance that PCA, as mentioned, despite being useful to group the effects of Environment-related variables and providing insight about the significance of BESG, concealed true individual effects of those variables instead. And we should say the individual effects behind the (E), as we did not consider here the (S) and the (G).

Back to the raw ESG variables, in fact, we may apply a simple ordinary least squares (OLS) regression to estimate:

$$\frac{dR}{dt} = \beta_0 + \beta_1 GHGs1 + \beta_2 TEC + \beta_3 TWU + \beta_4 TWa + \epsilon \tag{8}$$

where:

GHGs1 = GHG Scope 1.

TEC = total energy consumption.

TWU = total water use.

TWa = total waste.

This is how ESG variables impact revenues growth (see the table below): GHG Scope 1 (pollution) has a strong negative effect (−5965.43). This suggests that higher emissions are associated with lower revenue growth. By the same token total water use (−2054.01) and waste (−368.70) also negatively impact revenues. While total energy consumption has a strong positive effect (+9384.53), that is, more energy use correlates with higher revenue growth (which may reflect energy-intensive industries generating higher revenue) (Table 5).

Pollution, as a byproduct of higher production, may negatively impact Revenues Growth as a symptom of inefficiency. Low-tech productions, obsolete production processes, and even regulatory costs may provide an explanation. In other words, high-polluting firms may have structural inefficiencies that limit revenue growth. The most polluting industries are not the ones with the highest revenue growth rates. Further to this,

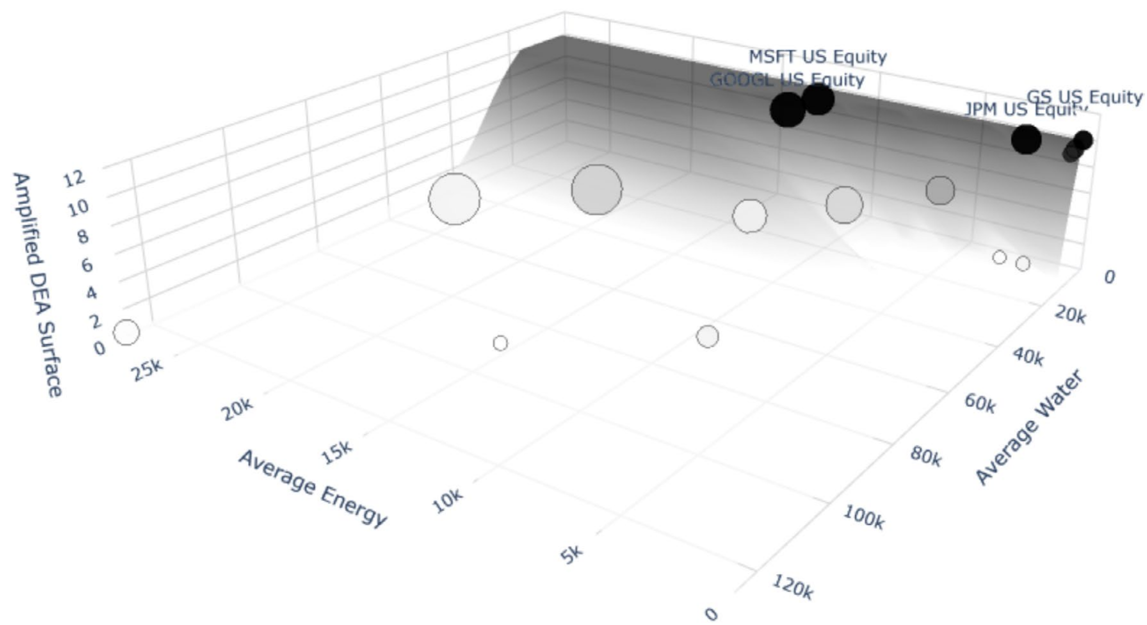

FIGURE 4 | DEA surface (bullets size = average revenues). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 | Estimated coefficients of final OLS equation.

	Coefficient
const	5145.54589
GHG Scope 1	−5965.432905
Total energy consumption	9384.531218
Total water use	−2054.005726
Total waste	−368.7037744

pushing consumers and investors to privilege green companies may amplify this effect.

In PCA, variables were combined into general sustainability components, potentially diluting individual ESG effects. When using raw ESG values, we now see stronger effects on revenue growth. This suggests an ESG trade-off: Growth vs. Sustainability. Higher energy use is associated with higher revenue growth, and this suggests that companies making more revenue might rely—not surprisingly—on high energy consumption.

Higher pollution, waste, and water use suggest lower revenue growth; on the other hand, this suggests that sustainability can be beneficial, but only in specific areas.

Strategy costs could matter even more, therefore: if sustainability costs money, and our model already suggests energy-heavy firms grow faster, then forcing ESG investments might reduce growth even further in the absence of explicit benefits from the reduction of GHG, Waste, and Water consumption.

7 | Concluding Remarks

The literature underscores the complex interplay between sustainability adoption, financial performance, technological transformation, and geopolitical risks. While prior studies suggest investor attention to ESG information and climate-related risks, the financial implications of sustainability investments remain sensitive to measurement choices and contextual conditions. Further research is needed to refine ESG assessment frameworks, address AI-related biases, and evaluate the geopolitical implications of sustainability commitments.

Our empirical findings challenge the assumption that ESG investments inherently drive financial performance. The empirical evidence primarily derived from PCA-based regression, supported by the preliminary dynamic modeling framework, suggests that while pollution (GHG emissions), water use, and waste production negatively impact revenue growth, energy consumption is positively associated with it. Notably, the Bloomberg ESG score did not contribute significantly to explaining revenue trends, indicating that current ESG ratings may not adequately capture the financial benefits of sustainability efforts.

Furthermore, additional simulations based on hypothetical cost-free environmental improvements (i.e., simulated reductions in emissions and resource use within the refined empirical model) revealed that even under a cost-free sustainability improvement framework, no revenue growth advantage was observed. This result *falsifies* the common assumption that environmental improvements always support growth. In our simulations, even aggressive emissions reductions—implemented at no cost—did not improve firm revenue growth. This suggests that in real-world conditions, where companies bear the financial burden of ESG investments, the trade-off between sustainability and profitability may be even more pronounced. The results imply that firms integrating ESG strategies must navigate efficiency constraints and cost structures carefully, as sustainability-driven improvements in emissions and resource consumption do not automatically translate into financial gains. Companies in resource-intensive industries show slower progress towards the benchmark ESG configuration, while technology and service-oriented firms display more consistent improvements over time. Compared with previous studies focusing on ESG scores or single-factor efficiency measures, this multidimensional approach captures interactions across environmental performance indicators, offering a more “holistic” view of corporate sustainability performance.

These findings reinforce the need for a more nuanced approach to ESG assessment, one that accounts for sectoral differences, regulatory impacts, and firm-specific characteristics, specifically as far as the environmental profile. Future research should explore whether alternative sustainability metrics, beyond aggregate ESG scores, can better predict long-term financial resilience and competitive advantage. Policy-wise, our results caution against treating aggregate ESG scores as sufficient statistics for firm performance; we recommend disaggregated E-metrics and sector-sensitive benchmarks for capital allocation and regulation.

Author Contributions

Maurizio Pompella: theoretical framework, conceptualization, investigation, methodology, formal analysis, writing (original draft), writing (review and editing). **Lorenzo Costantino:** theoretical framework, conceptualization, investigation, methodology, formal analysis, writing (original draft), writing (review and editing).

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] The COP29 meeting in Baku of the 2024 United Nations Conference of the Parties of the UNFCCC shed light on the hurdles to reach global consensus on policy remedies to climate change.

[2] Microsoft corporation committed to becoming carbon negative by 2030, and by 2050 to remove from the environment all the carbon the company has emitted either directly or by electrical consumption since its establishment in 1975.

[3] More specifically, we refer here to *ESG transition costs* as the costs that the enterprises have to face in order to reach an adequate and satisfactory sustainability level, and—as far as regulated matters—compliance. *Sustainability transition* is not a new issue in the literature, and it was already on the top in some research niches 10/15 years ago. See for instance Markard J., Raven R. and Truffer B., "Sustainability Transition: an Emerging field of research and its prospects", Research Policy, vol. 41, issue 6, July 2012.

[4] The announcement from S&P 500 of the revision of the ESG Index "The (Re)Balancing Act of the S&P 500 ESG Index", available at https://www.indexologyblog.com/2022/05/17/the-rebalancing-act-of-the-sp-500-esg-index/.

[5] Data were obtained from Refinitiv Workspace, ensuring consistency across environmental (E), social (S), and governance (G) pillars. All variables were standardized prior to the multivariate analysis to remove scale effects.

[6] This integrated PCA–Mahalanobis framework provides a methodological advancement over conventional ESG scoring systems, as it captures both direction and magnitude of divergence within a multidimensional sustainability space. The approach enables cross-sectional comparability and longitudinal tracking without relying on proprietary ESG weights.

[7] Finally, to better understand the economic meaning of each component and avoid interpretive ambiguity, we returned to the raw ESG variables in a standard OLS framework, simulating alternative policy scenarios (see below).

[8] Even if PC_2 has a strong loading (0.71) from waste in the PCA structure, it does not show as a significant driver in the dynamic equation for waste production. This suggests that although waste plays a central role in shaping the underlying ESG/GHG composite factors, its own time evolution is more directly driven by other components (like PC_1), or the effect of PC_2 on waste is collinear with PC_1 and absorbed by it. PC loadings describe how variables influence principal components, whereas regression coefficients explain how those components define the target variable, in fact.

[9] This is clearly shown in the graphs, specifically in the PC1 box.

[10] In our regression model, the coefficient of BESG Score was positive (+584.17), but not statistically significant ($p = 0.75$). This suggests that firms with higher ESG scores do not necessarily experience higher revenue growth. BESG Score may be more of a "Reputation Score" than a realistic Sustainability Investment indicator. Such kinds of ratings are influenced by disclosure practices and company policies, in fact. A company might score high on ESG simply because it reports more ESG data, maybe polluting a lot (heavy E), while performing well in terms of (S) and/or (G), not necessarily because it is improving sustainability performance.

[11] This is also confirmed by the (relatively) low percentage of variance explained by PC1-2-3, about 70%.

[12] That is: DEA provides a purely technical efficiency measure, telling how well inputs—for example, like energy or GHG—are used to produce revenues.

[13] Also, the following should be considered as well: DEA is strictly an input–output analysis, whereas BESG includes management quality, risk, and disclosure. On the other hand, if DEA is a purely technical efficiency measure, it is worth wondering which confidence degree is proper to assign to the plethora of publicly (and non) available rankings.

[14] Meaning that we used a smooth interpolation technique based on inverse radial basis functions $\phi(r) = 1/(1 + r$ (Berg et al. 2022)), to visualize the DEA efficiency surface across multiple dimensions.

[15] We skip a pre-emptive interpolation to test purely government-driven sustainability policies; otherwise, we should suppose the companies have different reactions to the incentives and firm strategies that could bias the result. If we would study how companies respond to ESG policies *while maintaining their strategies*, we should first interpolate, then impose ESG reductions. Here we chose not to interpolate future firm behavior in order to eliminate firm-specific responses from the test, with no internal firm dynamics taken into account.

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Appendix A

Two versions of the differential equations model: Before and After Adjustments, and DEA analysis.

Initial Assumptions and Their Origin

The original model was based on a combination of pure economic reasoning, theoretical insights from literature on sustainability and firm growth, and basic dynamical systems modeling. The primary assumptions were:

i. Revenue growth (R)
   - Firms grow over time, with growth influenced by pollution, energy consumption, waste, and water usage.
   - Higher pollution negatively impacts revenues (reputational damage, regulation, or operational inefficiencies).
   - Energy use, waste, and water consumption impose costs that limit growth.

ii. Pollution (P)
   - More production leads to more pollution.
   - Firms reduce pollution over time due to regulation and thanks to efficiency improvements.

iii. Energy consumption (E)
   - More production requires more energy.
   - Firms reduce energy use through efficiency investments.

iv. Waste (W) and water use (A)
   - More revenue means more waste and water consumption.
   - Firms improve efficiency over time, reducing these impacts.

These assumptions were largely intuitive and drawn from basic economic and environmental literature but lacked empirical validation from the dataset.

The First Version of the Initial Model and Its Assumptions

The original system of differential equations was:

Revenue growth equation:

$$\frac{dR}{dt} = \alpha - \frac{\beta P}{1+P} - \gamma E - \delta W - \varepsilon A \tag{A1}$$

Pollution dynamics (GHG Scope 1):

$$\frac{dP}{dt} = \lambda R - \rho P - \sigma P \tag{A2}$$

Energy consumption equation:

$$\frac{dE}{dt} = -\kappa R - \tau E \tag{A3}$$

Waste production equation:

$$\frac{dW}{dt} = -\psi R - \omega W \tag{A4}$$

Water consumption equation:

$$\frac{dA}{dt} = -\theta R - \iota A \tag{A5}$$

Variable Definitions and Parameters

Symbol	Meaning
R	Revenues (firm financial performance)
P	Pollution (GHG Scope 1 emissions)
E	Total energy consumption
W	Total waste produced
A	Total water consumption
α	Growth rate coefficient for revenue
K	Carrying capacity (maximum achievable revenue)
β	Impact coefficient of pollution on revenue
λ	Impact of revenue on pollution production
ρ	Pollution reduction coefficient
σ	Energy efficiency impact on pollution reduction
γ	Impact of energy consumption on revenue
μ	Impact of revenue on energy consumption
τ	Energy efficiency coefficient
ν	Impact of revenue on waste production
ω	Waste reduction coefficient
ξ	Impact of revenue on water consumption
ι	Water efficiency coefficient
η	External economic factors affecting revenue

- Linear revenue growth term (α): Assumed that firms could grow indefinitely, without a natural ceiling.
- Negative impact of sustainability variables on revenue: Pollution, energy, waste, and water were all assumed to directly reduce revenues.
- No self-limiting effects in revenue growth.
- Pollution reduction driven solely by regulatory factors (ρP and σP).
- Energy, waste, and water use assumed to decrease with revenue, which lacked empirical support.

Empirical Adjustments to the Model

After analyzing the dataset through trend analysis, correlation studies, and regression analysis, we identified critical misalignments:

Empirical Findings

1. GHG Scope 1 (pollution) weakly correlates with revenue (−0.645, $p = 0.084$). Pollution should still impact revenue, but the effect is weaker than initially assumed.
2. Total energy consumption correlates with revenue (0.012, $p = 0.977$). Energy usage scales with firm size, not necessarily inefficiency.

3. BESG score is exogenous. The sustainability score does not influence revenues directly, since it is externally assigned.

Step-by-Step Changes

1. Revenue growth equation
   – Introduced a logistic growth term (self-limiting revenue growth based on market constraints).
   – Weakened the impact of pollution based on the weak empirical correlation.
   – Removed waste and water from the revenue equation since their impact on revenue was unclear.
2. Pollution equation
   – Pollution still increases with revenue but now also decreases with energy efficiency investments.
3. Energy consumption equation
   – Energy consumption should grow with revenue but at a constrained rate.
4. Waste and water equations
   – Instead of assuming firms reduce these variables with more revenue, we now allow them to grow with revenue but at a slower rate.

The Model After the Adjustments

Refined revenue growth equation:

$$\frac{dR}{dt} = \alpha R \left(1 - \frac{R}{K}\right) - \frac{\beta P}{1 + P} - \gamma E + \eta \tag{A6}$$

Refined pollution dynamics (GHG Scope 1):

$$\frac{dP}{dt} = \lambda R - \rho P - \sigma E \tag{A7}$$

Refined energy consumption equation:

$$\frac{dE}{dt} = \mu R - \tau E \tag{A8}$$

Refined waste production equation:

$$\frac{dW}{dt} = \nu R - \omega W \tag{A9}$$

Refined water consumption equation:

$$\frac{dA}{dt} = \xi R - \iota A \tag{A10}$$

Differences Between the Two Models

Feature	Initial model	Final adjusted model
Revenue growth	Linear	Logistic growth (self-limiting)
Pollution effect on revenue	Strong	Weakened based on empirical findings
Energy consumption	Always decreasing	Scales with revenue but constrained
Waste and water consumption	Decreases with revenue	Increases with revenue but at a slower rate
BESG score	Modeled as endogenous	Treated as an exogenous variable