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ORIGINAL ARTICLE

Assessing the transition risks of environmental regulation in the United States: Revisiting the Porter hypothesis

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Abstract
The harmful effects of climate change have brought global warming into focus, prompting a growing body of research on its economic impact and the development of targeted climate policies aimed at mitigating these effects and promoting sustainability. Within this context, the main objective of this paper is to investigate whether the presence of transition risk drivers, in particular, the implementation of environmental policies in the United States, initiates risks or fosters green innovation and financial performance. This performance is related to the adjustment process toward a low-carbon economy, widely known as the Porter hypothesis. Using a panel threshold regression model over the period 1990–2020, our results show that market-based climate policies have a heterogeneous effect on the firm's green innovation and financial performance. Specifically, we find an inverted-U-shaped relationship between carbon price and firm outcomes including green innovation and financial performance. These findings have significant implications for practice, as they reveal the mechanism through which climate policies can optimally affect a firm's green innovation activity and financial performance.

KEYWORDS
climate policies, first-mover advantage, green innovation, Porter hypothesis, risk of bankruptcy, survival analysis, threshold regression, transition risk, transition risk drivers

1 | INTRODUCTION

Climate change is one of the defining "grand challenges" of our generation. Since the establishment of the United Nations Framework Convention on Climate Change in 1992, global awareness of its impacts has steadily increased. The severity of ecological and environmental issues related to climate change has brought global warming into the spotlight, prompting numerous studies to focus on the emission of greenhouse gases (Lamb et al., 2021). Global warming directly results from the accumulation of greenhouse gases (carbon dioxide, nitrous oxide, and methane) primarily from human activities (Michail et al., 2019). The consequences of climate change have become increasingly significant over the last decade (Polemis & Stengos, 2018; Kalaitzidakis et al., 2018). According to the Intergovernmental Panel on Climate Change (IPCC) (2021), global temperatures have risen substantially, particularly in the Northern Hemisphere and mid-latitudes. This has led to a range of physical risks, including rising sea levels, more frequent droughts and floods, hurricanes, cold snaps, and heat waves—all of which have severely impacted economic outcomes. Almost 200 countries joined the Paris Climate Agreement in December 2015, and more than 70 countries, including the biggest emitters (China, the United States, and the European Union) have communicated net-zero carbon emissions by 2050 (United Nations, 2022). A rapidly expanding body of research is focused on two key areas. The first focuses on evaluating the impact of climate change on economic activity (Dell et al., 2014; Carleton & Hsiang, 2016). The second aims to understand the mechanisms driving climate change, with the goal of designing, implementing, and, most importantly, evaluating the effectiveness of specific climate policies. Climate policies, legislation, and regulations are considered to be transition risk drivers, as they have the potential to generate financial risks associated with the transition towards a low-carbon economy (European Central Bank, 2022). Within this context, the main objective of this paper is to investigate whether the presence of transition risk drivers, specifically, the implementation of environmental policies in the United States initiates risks or fosters green innovation and financial performance related to the adjustment process toward a low-carbon economy. This concept is central to the Porter hypothesis, which suggests that well-designed environmental regulations can stimulate innovation and enhance firm competitiveness. The relationship between climate change and economic outcomes has traditionally been modeled using two alternative approaches: The first is using the Integrated Assessment Models (IAMs) and the second is based on a cross-section of countries. The IAMs pioneered by Nordhaus (1991, 1993) with the Dynamic Integrated model of Climate and Economy are characterized by their multidisciplinary nature (Weyant et al., 1996; Tol, 2002) and combine information about climate systems and human behavior to make projections about the future climatic change and its consequences. However, the IAMs have often been criticized for uncertainties related to the model structure and assumptions driving the results in model runs (Pindyck, 2013). Given these uncertainties, the second strand of literature uncovers the relationship between physical risks related with climate change (such as temperature, precipitation, or extreme weather events like windstorms, storms, droughts, cyclones, and hurricanes) and economic outcomes, including aggregate output, labor productivity, energy, agricultural production, commodity prices, health and mortality, conflict and political stability (Henseler & Schumacher, 2019; Hsiang, 2016; Letta & Tol, 2019; Stern, 2007) using a cross-section of countries.

The detrimental effects of climate change on economic outcomes have intensified the efforts for evaluating and developing long-run efficient climate policies (e.g., Schatzki & Stavins, 2018; Stavins, 2022). Researchers and governments worldwide acknowledge that climate policies trigger cost-effective pollution mitigation and are important stimulants for energy-efficient and low-carbon innovation. Research regarding the effects of climate policies on a firm's outcomes focuses primarily on the compliance cost (Barbera & McConnell, 1990) and on the Porter hypothesis (Porter, 1991; Porter & Linde, 1995a, 1995b). According to the compliance cost hypothesis, strict environmental regulations entail transition risks, since they increase costs for compliant enterprises and crowd out any capital investments that could have been used for innovation (Faucheux & Nicolaï, 1998). Therefore, environmental policies can delay technological innovation, and may be the cause of a loss on the competitiveness of firms (Albrizio et al., 2017). In contrast, the Porter hypothesis states that there are no transition risks associated with environmental regulations because of the cost pressure underlying environmental policies which will inevitably drive firms to focus on innovation (including green innovation) with benefits exceeding the compliance cost. Thus, environmental policies are expected to be a "win–win" strategy for the firms. In the literature, the Porter hypothesis is divided into the "weak" version, which is focused on the effect of environmental regulation on innovation; the "strong" version, which is focused on the competitiveness and productivity of the firms; and the "narrow" version, which supports that flexible environmental policies (market instruments) increase the firm's incentives to innovate, being more effective than prescriptive (nonmarket instruments) forms of regulation (Ambec et al., 2013).

Focusing on the "weak" version of the Porter hypothesis and the relationship between environmental policies and green innovation, the rationale dates back to Hicks (1932). Hicks (1932) supports that when environmental regulations raise the cost of pollution relative to other costs of production, firms have a significant incentive to focus on developing new technologies reducing emissions. Porter and Linde (1995a) later developed this idea further, formulating the "Porter hypothesis." This hypothesis suggests that environmental policies can induce innovation through the following channels: (i) regulations signal firms about potential resource inefficiencies and innovation opportunities; (ii) policies focused on information gathering provide significant benefits by raising corporate awareness; (iii) regulations reduce uncertainty by ensuring that investments to address environmental issues will be important; (iv) regulations apply pressure on firms, driving innovation and progress; and (v) regulations ensure that during the transition to innovation-based solutions, firms cannot gain a competitive advantage by avoiding green investments. Therefore, in this context of weak version of the Porter's hypothesis, environmental regulations promote efficiency and cost savings for firms by encouraging them to adopt more sustainable practices, eliminating any transition risks.

There is a growing literature investigating the impact of environmental regulation on green innovation at the firm and country levels (e.g., Aghion et al., 2016; Dechezlepretre & Sato, 2017; Rubashkina et al., 2015; Z. Wang et al., 2022). Overall, these studies support the notion that stricter environmental regulations can induce green innovation. However, Z. Wang et al. (2022) point out that the impact of environmental regulations on green innovation has not attracted enough attention, since past literature focused on using linear models, when there are indications accounting for the existence of parameter heterogeneity and in particular, for the presence of an inverted U-shaped relationship between environmental policies and green innovation. Specifically, the initial implementation of mild climate policies will not create any investment pressure on the firms which will choose to increase green innovation in response to the call of the policy (Dong & Wang, 2019). However, when the government imposes strict climate policies, it induces significant transition risks with subsequent negative effects on green innovation. Under this regime, firms will be discouraged to engage in green innovation, since it is considered as risky, and costly; thus, firms will choose to abandon such an investment choice to reduce production costs and risks (Falcone, 2020). Therefore, climate policies have a nonlinear effect on green innovation since mild climate policies tend to positively influence green innovation, while the introduction of stricter environmental regulations significantly raises production costs and risks, ultimately hindering green innovation initiatives.

The crucial question is at what threshold climate policies begin to impose a burden on firms, and how, based on this estimated threshold, policymakers can design and implement effective climate policies that foster green innovation and growth. The estimation of a threshold regression model is aiming to capture the nonlinear relationship between climate policies and green innovation and provide, to the best of our knowledge, for the first time specific answers to these important questions.

Therefore, the first objective of this paper is to fill this gap by investigating the "weak" Porter hypothesis regarding the impact of transition risk drivers and in particular, climate policies on green innovation in a nonlinear setting using a threshold regression model.

Furthermore, there is a significant body of literature investigating the "strong" version of the Porter hypothesis on the impact of environmental regulation transition risks on the firm's competitiveness and productivity. Brandt et al. (2012) and Tombe and Winter (2015) support the presence of a direct effect of environmental policies on the firm's performance through an optimal resource allocation and the elimination of backward production capacity. Nonetheless, environmental policies indirectly affect the firm's financial performance via the mediating mechanisms of "innovation compensation effect" and "first-mover advantage." Based on the "innovation compensation effect," firms facing increased costs because of stricter environmental regulations may offset these by developing newer and more efficient technologies, which will lead to higher productivity, cost savings, and competitive advantages, improving the firm's financial performance (Porter & Linde, 1995b). The "first-mover advantage" refers to the gains the firm gets when being the first to enter a particular market or adopt a new innovation (Lieberman & Montgomery, 1988). Strict environmental regulations encourage firms to implement new production modes with lower energy consumption and emissions through imitation innovation or independent innovation. The subsequent energy efficiency, production optimization, and reduction in costs can generate an innovation compensation effect eliminating any transition risks. The introduction of capital to generate innovation will enhance the accumulation of experience and resources, affecting the firm's competitiveness, profitability, value, and productivity (Lei et al., 2022; Zhao et al., 2022). Furthermore, the implementation of high-efficiency, low-energy production methods enhances a company's image among stakeholders, including consumers and the government. Specifically, through first-mover advantages, firms that provide environmentally friendly and energy-saving products can expand into new markets, strengthen their corporate reputation, and improve financial performance (Lei et al., 2022). Therefore, the presence of mild environmental policies has a robust positive effect on the firm's financial performance.

However, the existing findings regarding the strong Porter hypothesis are controversial, a fact that supports the presence or absence of transition risks (Berman & Bui, 2001; Cagatay & Mihci, 2006; Denison, 1981; Hamamoto, 2006; Hering & Poncet, 2014; Peuckert, 2014; H. Wang et al., 2019). While this research stream highlights the presence of parameter heterogeneity or nonlinearities, surprisingly, the empirical literature on the effect of environmental policies on the firm's financial performance focuses only on linear models. Based on the literature findings, we posit that while mild environmental policies have a positive effect on the firm's financial performance, the introduction of stricter climate policies significantly increases the costs and risks for firms, affecting directly or indirectly (through green innovation) their financial outcomes, including profitability, firm value, and risk of default. We attempt to fill this gap in the literature by uncovering the nonlinear relationship between climate policies and the firm's financial performance, taking into consideration the mediating mechanism of the "innovation compensation effect" in the context of a threshold regression model.

Therefore, the second objective of this paper is to evaluate the "strong" Porter hypothesis regarding the effect of transition risk drivers and in particular, climate policies on the firm's financial performance, value and risk of default through the mediating mechanism of "innovation compensation effect" in the context of a threshold regression model.

Focusing on climate policies, policymakers and governments have implemented a variety of market-based and non–market-based policies (J. Jiang et al., 2023) to combat climate change (Fawzy et al., 2020). Market-based policies aim to use market mechanisms to create economic incentives for reducing greenhouse gas emissions. On the other hand, non–market-based policies rely on regulations and government intervention to encourage emissions reductions and attain similar objectives (Ambec et al., 2013). While each approach has its own advantages and disadvantages, the effectiveness of both market-based and non–market-based policies depends on several factors, including the political and economic context in which they are implemented (Dasgupta et al., 2017). Therefore, it is crucial to carefully consider the trade-offs of both market-based and non–market-based policies to develop comprehensive and effective strategies to mitigate greenhouse gas emissions and address climate change.

Regarding the market-based policies, there has been considerable discussion in the literature focusing on their effectiveness in reducing greenhouse gas emissions (X. Guo et al., 2021). Broadly speaking, the market-based policies use economic incentives, such as taxes or cap-and-trade systems, to encourage the reduction of greenhouse gas emissions. Accordingly, the underlying principle of these policies is to establish a market-driven stimulus for lowering carbon emissions, accomplished by increasing their cost. The literature suggests that market-oriented policies offer several benefits over non–market-oriented policies. For instance, they provide flexibility to firms to reduce emissions in a manner that aligns with their production processes. Market-based policies also allow firms to choose the most cost-effective methods to reduce emissions, resulting in an efficient allocation of resources (Stavins, 2010). Nonetheless, market-oriented policies also possess certain limitations and their success is contingent on the challenging choice of an accurate price for the carbon emissions. Overall, prior research suggests that market-based policies can be more efficient, because they create financial incentives for companies to reduce their emissions (Fabrizi et al., 2018). However, these policies can be difficult to implement compared to non–market-based policies, such as regulations and subsidies. While non–market-based policies may not be as efficient, they are often more politically feasible.

Based on the above argument, this paper focuses on market-based policies. Despite the ongoing discussions among policymakers and environmental advocates, the United States has not yet implemented a national carbon tax policy. Therefore, our investigation utilizes the cap-and-trade system, which has been established to impose binding emission reduction targets. Specifically, this system sets a limit on the overall amount of greenhouse gas emissions that can be released. Firms are required to buy or sell allowances based on whether they have a shortage or surplus of allocated emissions compared to their verified emissions in order to comply with the cap (Stavins, 2008). Consequently, firms that manage to reduce their emissions below their permitted levels can sell their unused allowances to other companies. Overall, the cap-and-trade system provides a financial incentive for firms to lower their emissions at a lower cost than other regulatory methods (Schatzki & Stavins, 2018), while also serving as a disincentive for those firms that fail to reduce their emissions and must purchase additional permits, incurring extra costs. Ultimately, the effectiveness of various approaches to reduce emissions hinges on how well they incentivize firms to adopt cleaner technologies and practices.

This paper extends and contributes to the existing literature on the Porter hypothesis in several ways. First, it provides the first empirical examination of the weak and strong Porter hypotheses using US data, including 33,219 firm–year observations over the period 1990–2020. Second, it responds to the recent calls for further research on the heterogeneous effect of climate policies on green innovation and the presence of transition risks, by employing a purely nonlinear setting in the context of the threshold regression model. Third, using the same nonlinear setting, it assesses the impact of climate policies on the firm's financial performance exploring at the same time, the mediating effect of "innovation compensation effect." Fourth, the paper ensures the robustness of the results under different model specifications, including a bounding method proposed by Oster (2019), which examines the presence of omitted variable bias, an investigation of the impact of structural breaks (see Karavias et al., 2022) and financial constraints, and the possibility of the presence of a moral hazard problem using a semi-quantitative approach. Finally and most importantly, the findings of this study have significant implications for practice, as they reveal the mechanism through which climate policies may optimally affect the firm's green innovation practices and its financial performance, eliminating the adverse effects of transition risks. The empirical results provide, for the first time, an answer to the question of what threshold point exists where climate policies become a burden for a firm's innovation and performance. Based on the estimated threshold, policymakers may design and implement appropriate climate policies that promote green innovation and financial growth.

2 | METHODOLOGY

2.1 | Threshold regression model

The effect of market-based climate policies on green innovation in the context of the weak Porter hypothesis is typically investigated following the theoretical framework of the knowledge production function proposed by Griliches (1979, 1990) and is based on a panel fixed effects model,

$$y_{it} = \mu_i + \beta' x_{it} + e_{it}, \tag{1}$$

where the dependent variable y_{it} is a scalar and measures green innovation, x_{it} is a $k \times 1$ vector of green innovation determinants including market-based climate policies and firm characteristics, β is a $k \times 1$ vector of unknown parameters, e_{it} is an error term for firm $i = 1, 2, \ldots, N$ and time $t = 1, 2, \ldots, T$.

This study extends the linear framework and builds on previous literature (Fabrizi et al., 2018; Ghisetti et al., 2015; Ghisetti & Pontoni, 2015; Z. Wang et al., 2022) to consider a green knowledge production function estimated using the panel threshold regression model with interactive fixed effects (Hansen, 2000, 2017; Kourtellos et al., 2016; Miao et al., 2020) to control for cross-sectional dependence. This model allows for the presence of multiple regimes based on a certain threshold variable q_{it},

$$y_{it} = \begin{cases} \mu_i + \beta_1' x_{it} + e_{it}, \ q_{it} \le \gamma \\ \mu_i + \beta_2' x_{it} + e_{it},, \ q_{it} > \gamma \end{cases}, \tag{2}$$

where γ is the scalar threshold parameter or sample split value and (β_1', β_2') is the vector of regression coefficients for the low and high regime, respectively. Therefore, this model evaluates the heterogeneous effect of market-based climate policies on green innovation based on different climate policy regimes. Alternatively, Equation (2) can be also expressed in a single equation as,

$$y_{it} = \mu_i + \beta_1' x_{it} I(q_{it} \le \gamma) + \beta_2' x_{it} I(q_{it} > \gamma) + e_{it}, \tag{3}$$

where $I(.)$ is the indicator function. Estimation of the model requires to identify if the threshold effect is statistically significant, thus, following Seo and Shin (2016), we implement a bootstrap test based on a supremum Wald statistic for the null hypothesis of a linear model. In practice, we first test for the presence of a nonlinear relationship between market climate policies on green innovation by estimating the particular threshold/turning point, and then, we uncover the impact of market-based climate policies on green innovation under the different climate policy regimes by estimating a panel threshold model.

Regarding the strong version of the Porter hypothesis and the impact of climate policies on the firm's profitability and firm value, we also employ the panel threshold regression model to uncover the possible heterogeneous effect of market climate policies on the firm's profitability and firm value.

Finally, to assess the impact of climate policies on the probability of bankruptcy due to default, we first test for the presence of threshold effects for binary outcomes following Lee et al. (2011) and subsequently, we estimate a discrete hazard model in the form of a multiperiod logit (Campbell et al., 2008; Shumway, 2001), which is typically employed to analyze unbalanced data, including firm defaults, with time-varying covariates given by,

$$\Pr\left(y_{it}=1\right)=\Phi\left(\mu_i+\beta_1' x_{it}+e_{it}\right) = \frac{1}{1+exp\left[-\left(\mu_i+\beta_1' x_{it}+e_{it}\right)\right]}, \tag{4}$$

where y_{it} is a dummy that indicates corporate bankruptcy because of default. The variable takes the value of 0 if the firm is active and the value of 1 if the firm is bankrupt due to default. Default indicates that a debtor has not served its debt obligations, while bankruptcy is a legal mechanism imposing court supervision over the financial affairs of those who are in default.

2.2 | Duration models

An additional way of evaluating the risk of default is to consider not only if firm i goes bankrupt due to default on a given time t, but also to assess the duration to default using survival analysis (Thomas et al., 2002). Within this context, we are interested in the timing T of bankruptcy due to default, and the associated survival function $S(t) = P(T > t)$, which reflects the probability of not experiencing bankruptcy due to default by time t. The associated probability density function can be expressed as $f(u) = -\frac{d}{du}S(u)$ whereas the hazard function,

$$h(t)=\lim_{\tau\to 0}\frac{P(t\le T<t+\tau|T>t)}{\tau}, \tag{5}$$

models the instantaneous risk of bankruptcy due to default at time t, given that it has survived until time t. The hazard function can also be expressed in terms of the survival function $h(t) = \frac{f(t)}{S(t)}$. In our analysis, a proportion of firms have not experienced bankruptcy due to default and thus, are censored. Following the literature (Bonfim, 2009; De Leonardis & Rocci, 2008; Kim et al., 2016; Kristanti & Herwany, 2017; Tong et al., 2012), we initially estimate the semiparametric Cox proportional hazards model (Cox, 1972) defined from the following hazard function with time-varying covariates,

$$h\left(t/Z\left(t\right)\right)=h_0\left(t\right)\exp\left(\beta' x+\gamma'\chi g\left(t\right)\right), \tag{6}$$

where $h_0(t)$ is a nonparametric baseline hazard function and β' and γ' are coefficients of time-fixed and time-varying covariates, respectively. To explore the robustness of our results we also consider two parametric accelerated failure time models, the Weibull and the Loglogistic, whereby the explanatory variables act as acceleration factors to speed up or slow down the survival process as compared to the baseline survival function. The choice of the particular survival models was based on the findings of Dirick et al. (2017), who examine the performance of alternative survival techniques using financial data.

Further, to tackle any endogeneity concerns related to reverse causality/simultaneity bias and omitted variables (Wooldridge, 1997) leading to incorrect inferences (Abdallah et al., 2015), all empirical models are estimated using IV/two-stage least squares (2SLS), where all endogenous variables are instrumented using their corresponding 5-year lag-values.[1]

2.3 | Data

We have employed four datasets for this study's analysis; green innovation data from the US Patent and Trademark Office (USPTO), market-based climate policies for the United States from the World Carbon Pricing Database, firm financial data from Compustat, and CEO variables from execucomp.

Following the Patent Assignment Dataset Schema, we first combined assignee information (including company name and address) with innovation data (patents, invention title, application, and granted date) and the US Patent Application Publication dataset, which includes a detailed patent classification. For our analysis, we considered innovation data based on the Cooperative Patent Classification, and particularly patents that are classified under the "technologies or applications for mitigation or adaptation against climate change" scheme, which is aligned with the framework of the Kyoto Protocol and the Paris Agreement (USPTO). Subsequently, green innovation data from USPTO were merged with the Compustat dataset by utilizing fuzzy-string matching techniques (Bena et al., 2017; Graham et al., 2018) to create links between the innovation assignee strings extracted from the USPTO and the firms' name strings extracted from Compustat. Finally, compiling information from the World Carbon Pricing Database, we have included a market-based climate policy based on the cap-and-trade scheme. Our final sample consists of 33,219 firm–year observations over the period 1990–2020.

Following the literature (Aghion & Jaravel, 2015; Y. Jiang & Chen, 2018; Z. Li et al., 2020), we proxied green innovation using the natural logarithm of the number of

[1] In all first-stage regressions, we estimate the Stock and Yogo (2005) weak instruments F-statistic. In all cases, the reported F-statistic is greater than 10 ensuring that the instruments are not weak. In addition, the results are robust under alternative lag specifications. The first-stage tests and the alternative lag specifications results are available upon request.

green granted patents +1 (Ln (Patent+1) to avoid losing observations with zero green granted patents.

To access the impact of the climate policies in the United States, we gather Carbon-Pricing Policies data from World Carbon Pricing Database based on the state cap-and-trade system because the United States currently does not have a carbon tax at a national or state level. In particular, we use state emissions-weighted carbon price, in 2019$/tCO which is the average carbon price across all sectors of a jurisdiction's economy, weighted by each sector's share of the economy's total emissions.

Our control variables include a set of various firm-specific characteristics, including firm size, firm growth rate, asset structure, current and solvency ratio, leverage, and R&D expenditure. The model controls for firm size by considering both the natural logarithm of the company's revenue and the natural logarithm of total assets, since bigger firms are able to secure external finance for their projects (Z. Chen et al., 2021; K. Li et al., 2019). Further, the ratio of the intangible assets to total assets, controls for the firm's rate of growth. Firms characterized by accelerated growth rates, may find it difficult to fund their growth with just internal funds and, thus, they rely heavily on external finance (Stanworth & Curran, 1976). The dependence on external debt increases the cost of capital, forcing managers to finance only high yield projects and to forego projects that are low in profitability, but perhaps vital for the firm's long-term viability. Thus, high growth firms cannot secure easily additional funding, causing a decrease on their innovation output. Daskalakis and Psillaki (2008) and Psillaki and Daskalakis (2009) emphasize that the asset structure of a firm (ratio of its fixed assets to total assets) is an important determinant of external finance because firms with high ratios are able to safeguard their lenders from adverse selection and moral hazard problems, by providing collateral as a security of additional and at the same time cheaper loans to fund their projects (Kumar et al., 2017; Ramli et al., 2019). In addition, the current ratio (current assets to current liabilities) and solvency ratio (ratio of long-term debt to long-term assets) reflect the ability of the firm to repay short-term and long-term obligations. Insolvent firms are generally less able to secure low-cost funding; therefore, they are less able to fund additional innovation projects. Furthermore, the leverage ratio (long-term debt divided by shareholders' equity) reflects the firm's capacity to take on additional debt. Higher values of this ratio increase the firm's financial burden, compelling it to fund only innovation projects with high returns, thereby avoiding lower yield projects related to innovation. Finally, the role of R&D expenditure, which are vital for firms to develop new knowledge, invent and innovate (Alexy et al., 2013; Mudambi & Swift, 2014) is also considered, and is calculated as the ratio of R&D expenditures divided by sales. To control for any unobserved heterogeneity we use year, state, and industry fixed effects.

Regarding the second objective of this study, which focuses on the strong version of the Porter Hypothesis, we employed return on assets (ROA) as a proxy for firm profitability and Tobin's Q as a proxy for firm value. ROA was calculated using earnings before interest and taxes scaled by the firm's total assets, whereas Tobin's Q based on the firm's market value of assets divided by its book value of assets. In addition, following Cathcart et al. (2020), we construct the firm's bankruptcy due to default history using the "status" and "status date" provided by Compustat. Table 1 in the Supporting Information Appendix reports summary statistics for all the variables included in the analysis.[2]

TABLE 1a Threshold tests and threshold estimates for green innovation.

Threshold variable	*p*-value	Threshold
Carbon price (single threshold)	0.0010	5.0
Carbon price (double threshold)	0.6830	3.7

Note: This table presents the threshold test with the corresponding *p*-value and threshold estimate for green innovation for the null hypothesis of a linear model against the alternative of a single and double threshold.

3 | EMPIRICAL RESULTS

3.1 | Transition risk drivers and green innovation

The primary aim of this paper is to investigate the weak Porter Hypothesis by examining the effectiveness of climate policies in stimulating green innovation in a nonlinear setting using a threshold regression model. In other words, we examine if the implementation of transition risk drivers and in particular, certain environmental policies (cap-and-trade carbon prices), triggers the production of green patents and gradually eliminates the presence of any related transition risks.

Within this context, we first need to identify the nature of the relationship, whether it is linear or nonlinear, between climate policies (carbon price) and green granted patents using a threshold test. The empirical findings suggest in general that the effect of environmental policies on green innovation is positive (e.g., Aghion et al., 2016; Rubashkina et al., 2015); however, recent literature (Z. Wang et al., 2022) reveals that the effect is heterogeneous and hence, under certain conditions the implementation of environmental policies introduces significant transition risks related to a great extend with additional costs.

Table 1a shows the results of the threshold test considering the presence of one and two thresholds. The first column of the table shows the number of thresholds/splits under consideration for carbon price, then the corresponding *p*-value for the null hypothesis of a linear model against the alternative of a threshold, along with the corresponding threshold estimate.

[2] To tackle any issues of nonstationarity, which would lead to spurious regression affecting coefficients, standard errors, and the relevant R^2, we follow Karavias and Tzavalis (2014) and a panel unit root test for the null hypothesis of a random walk with drift against the alternative of a stationary panel process with unknown structural breaks in the intercepts and linear trends at time *b*, was implemented. According to the findings, the null hypothesis of nonstationarity is rejected. The results are available upon request.

TABLE 1b Threshold regression-green innovation.

			Threshold regression model			
	Linear Model		Low carbon price regime ≤5		High carbon price regime >5	
	(1)	(2)	(3)	(4)	(5)	(6)
Variable	Coef.	SE	Coef.	SE	Coef.	SE
Carbon price	0.0212***	0.0057	0.0643***	0.0105	−0.0231**	0.0109
Size (revenue)	0.0091*	0.0052	0.0062	0.0051	0.0366*	0.0199
Size (assets)	0.0967***	0.0097	0.0889***	0.0096	0.0991**	0.0388
Growth	0.0057	0.0744	−0.0900	0.0684	−0.2469	0.3142
Asset structure	0.0853*	0.0518	0.0025	0.0426	0.2171	0.2628
Current ratio	0.0025***	0.0008	0.0001	0.0000	0.0007	0.0024
Solvency ratio	−0.0000	0.0000	−0.0000***	0.0000	−0.0001***	0.0000
Leverage	−0.0002***	0.0001	−0.0002***	0.0001	−0.0009	0.0009
R&D expenditure	0.0003***	0.0001	0.0004***	0.0001	0.0003***	0.0001
Constant	−0.2090***	0.0275	−0.2215***	0.0307	−0.0939	0.1573

Note: This table presents the linear and the threshold regression model estimation results for green innovation. The first and second columns include the coefficient and robust standard errors for the linear panel fixed effects model, whereas the remaining columns the threshold regression estimation results (coefficients and robust standard errors for the low and high regime). All endogenous variables are instrumented using their corresponding 5-year lag-values. All specifications always include year, state, and industry fixed effects.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

According to the results (p-value = 0.0010), the linear model null hypothesis is strongly rejected for the presence of one threshold/split when carbon price equals to 5. On the other hand, the p-value for the presence of a second threshold/split equals to 0.6830 and thus rejected, a result which was robust under different model specifications. Justifiably, then, it can be inferred that "there is a nonlinear relationship between carbon prince and green innovation.

Table 1b shows the threshold regression estimation for the two regimes. The first and second column illustrates the regression coefficient and the corresponding robust standard errors for the linear fixed effects panel model, whereas the remaining columns present the regression coefficients and robust standard errors for the low (below and equal to 5) and high (above 5) carbon price regime respectively, in the context of a panel threshold model. Regarding the effect of carbon price on green patents in the linear fixed effects model, carbon price has a positive effect on green innovation (0.0212) with significance of 1% confirming the theoretical predictions and previous empirical literature (Brunnermeier & Cohen, 2003; Carrion-Flores & Innes, 2010; De Vries & Withagen, 2005; Johnstone et al., 2010; Kneller & Manderson, 2012; Lanoie et al., 2011; Lee et al., 2011; Popp, 2003, 2006; Z. Wang et al., 2022).

However, applying the panel threshold model emphasizes the presence of parameter heterogeneity in the sense that the effect of carbon price on green patents is not exactly positive as in the linear model but, rather, it depends on the level of carbon price (below or above 5), yielding a nonlinear relationship between carbon price and green patents in the form of an inverted-U-shaped curve. In particular, when the carbon price is below or equal to 5, the effect on green innovation is positive (0.0643) and statistically significant (1%), but when carbon price is above 5, the impact is negative (−0.0231) indicating that stricter environmental policies introduce significant additional costs related with the adjustment toward a low-carbon economy (transition risks). Regarding the control variables, the findings confirm the expected positive impact of size, asset structure, current ratio and R&D expenditure and also, the negative effect of the solvency ratio and leverage on green innovation. The results confirm the theoretical predictions of the weak Porter hypothesis only in the presence of mild environmental regulations and have significant policy implications indicating the exact carbon price value which enhances green innovation performance.

3.2 | Transition risk drivers and financial performance

The second objective of this paper is to explore the strong Porter hypothesis by examining the effect of transition risk drivers, particularly climate policies, on a firm's financial performance, specifically profitability, firm value, and risk of default leading to bankruptcy. This is done through the mediating mechanism of the "innovation compensation effect" within the framework of a threshold regression model. The existing literature findings are controversial supporting the presence or absence of transition risks (e.g., Cagatay & Mihci, 2006; Hering & Poncet, 2014; Peuckert, 2014; H. Wang et al., 2019, among others) indicating that the heterogeneous effect of environmental policies on the firm's financial performance should be modeled in a nonlinear setting.

Table 2a presents the results of the threshold test for firm financial performance, proxied by ROA, considering the presence of one and two thresholds for the carbon price. The table includes the number of thresholds/splits, the corresponding

TABLE 2a Threshold tests and threshold estimates for return on assets (ROA).

Threshold variable	*p*-value	Threshold
Carbon price (single threshold)	0.0002	8.0
Carbon price (double threshold)	0.6739	4.3

Note: This table presents the threshold test with the corresponding *p*-value and threshold estimate for ROA for the null hypothesis of a linear model against the alternative of a single and double threshold.

p-value for the null hypothesis of a linear model versus the alternative of a threshold, and the threshold estimate.

Similarly to our previous results on the effect of carbon prices on green innovation, the results of the linear model null hypothesis is strongly rejected for the presence of one threshold/split (*p*-value = 0.0002), when carbon price equals to 8, confirming that that there is a nonlinear relationship between environmental policies and financial performance. Further, the presence of a second threshold/split is rejected (*p*-value = 0.6739).

Table 2b shows the threshold regression estimation for the two regimes. The first and second column illustrates the regression coefficient and the corresponding robust standard errors for the linear fixed effects panel model which is decisively rejected, whereas the remaining columns (3–6) present the regression coefficients and robust standard errors for the low (below and equal to 8) and high (above 8) carbon price regime, respectively, in the context of a panel threshold model. The linear fixed effects panel model confirms the findings of Brandt et al. (2012) and Tombe and Winter (2015) who identified a positive direct effect of environmental policies on firm's financial performance through an optimal allocation of resources and an elimination of backward production capacity. Nevertheless, applying the panel threshold model uncovers the presence of parameter heterogeneity, indicating that the effect of carbon price on financial performance (ROA) is not positive, as suggested by the linear model. Instead, it depends on the level of the carbon price (below or above 8), resulting in a nonlinear relationship between environmental regulation and firm profitability, forming an inverted U-shape-an empirical finding not previously considered. In particular, all else being equal, relatively mild environmental policies (carbon price below or equal to 8) have a positive effect (estimated coefficient 0.0725 and statistically significant at the 5% level) on the firm's profitability, offsetting in that way any transition risks. However, when the government imposes stricter climate policies, it induces significant transition risks; thus, the effect of carbon price on ROA is negative (estimated coefficient −0.0974 and statistically significant at the 1% level). Regarding the effect of the control variables, higher levels of firm size, asset structure, current ratio and R&D expenditure have a positive impact on ROA, whereas the effect of leverage is negative.

Our findings reveal the mechanism by which climate policies influence a firm's financial performance, offering an explanation for the mixed results in previous literature that relied on linear model estimates (Jaffe et al., 1995; Koźluk & Zipperer, 2013; Rubashkina et al., 2015). Environmental policies affect also the firm's financial performance indirectly via the mediating mechanism of "innovation compensation effect." As indicated earlier, green innovation fosters innovation compensation and improves the firm's financial performance by optimizing production processes, enhancing production technology and improving energy efficiency (Lei et al., 2022). Following Baron and Kenny (1986), to confirm the partial mediating effect of green innovation, three requirements need to be established: (i) environmental policies influence green innovation; (ii) environmental policies impact the firm's financial performance; and (iii) both environmental policies and green innovation affect the firm's financial performance. Tables 1b and 2b (Equations 1–6) confirm that carbon prices have an impact on the firm's green innovation and ROA, respectively.

In Table 2b, specifically in columns 7–12, we explore the simultaneous effect of climate policies and green innovation on financial performance (ROA). The threshold test for the extended model including green innovation confirmed the previous findings, estimating the same threshold point for carbon price and rejecting the presence of a double threshold.

In columns 7–8, the linear fixed effects panel model is presented, while in columns 9–12, the regression coefficients and robust standard errors are provided for the low (below and equal to 8) and high (above 8) carbon price regime, respectively, in the context of the panel threshold model. According to the results, carbon price and green innovation affect positively ROA, corroborating previous findings as well as confirming the partial mediating role of innovation. Considering the panel threshold model results, green innovation has a significant positive mediating effect in both regimes, whereas carbon price validating the previous findings has a heterogenous effect on ROA.

To further investigate our findings, we also estimate the effect of carbon price on the firm's value proxied by Tobin's Q. First, we test for the presence of nonlinearities using a threshold test presented in Table 3a.

The results confirm the previous findings that the relationship between environmental policies and firm value (Tobin's Q) is nonlinear based on a single threshold. Interestingly, the estimated threshold point equals to 9.5 which is marginally higher than the one identified in the test of financial performance (ROA). Table 3b illustrates the corresponding model estimation. In detail, in columns 1–2, we include the linear panel fixed effects model, whereas in columns 3–6, the threshold regression model results. It is evident that the implementation of environmental policies has a positive effect on the firm value (the estimated coefficient equals to 0.1500 and 1% statistically significant); nonetheless, when we consider the threshold regression results, the impact is heterogenous with a positive effect in the low carbon price regime (below and equal to 9.5) and negative in the high regime (above 9.5), supporting that stringent environmental polices induce significant transition risks for firms including high costs. The results are robust when we include green innovation in the model specification, verifying its medi-

TABLE 2b Threshold regression-return on assets (ROA).

			Threshold regression model						Threshold regression model			
	Linear model		Low carbon price regime ≤8		High carbon price regime >8		Linear model		Low carbon price regime ≤8		High carbon price regime >8	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Variable	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**
Carbon price	0.0275**	0.0111	0.0725**	0.0289	−0.0974***	0.0315	0.0342***	0.0110	0.1371***	0.0277	−0.0983***	0.0313
Green innovation	–	–	–	–	–	–	0.1434***	0.0315	0.0646**	0.0286	0.0503***	0.0151
Size (revenue)	0.1441***	0.0196	0.1562***	0.0190	0.0270	0.0616	0.1423***	0.0198	0.1541***	0.0192	0.0281	0.0525
Size (assets)	0.0661	0.0527	0.0443	0.0506	0.6914*	0.3924	0.0800	0.0554	0.0573	0.0529	0.6953***	0.0826
Growth	0.3421	0.2795	0.3552	0.2806	0.2455	0.6775	0.3117	0.2733	0.3165	0.2738	0.2366	0.6383
Asset structure	1.2239**	0.5616	1.2161**	0.5628	1.0346	0.7559	1.2133**	0.5590	1.1995**	0.5594	1.0478**	0.5200
Current ratio	0.0168***	0.0047	0.0172***	0.0050	0.0032	0.0089	0.0164***	0.0047	0.0169***	0.0050	0.0032	0.0080
Solvency ratio	−0.0045	0.0033	−0.0055	0.0042	−0.0003	0.0003	−0.0045	0.0032	−0.0055	0.0042	−0.0003**	0.0001
Leverage	−0.0003*	0.0001	−0.0003*	0.0002	−0.0004***	0.0001	−0.0003*	0.0001	−0.0003*	0.0002	−0.0007***	0.0001
R&D expenditure	0.0001***	0.0000	0.0002***	0.0001	0.0001*	0.0000	0.0001**	0.0000	0.0001***	0.0000	0.0001**	0.0000
Constant	−0.7659***	0.0647	−0.7104***	0.0648	−3.3930**	1.4096	−0.7968***	0.1960	−0.7396***	0.1910	−3.3754***	0.5017

Note: This table presents the linear and the threshold regression model estimation results for ROA. Columns 1, 2, 7, and 8 include the coefficients and robust standard errors for the linear panel fixed effects model, whereas the remaining columns the threshold regression estimation results (coefficients and robust standard errors for the low and high regime). All endogenous variables are instrumented using their corresponding 5-year lag-values. All specifications always include year, state, and industry fixed effects.

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 3a Threshold tests and threshold estimates for Tobin's Q.

Threshold variable	*p*-value	Threshold
Carbon price (single threshold)	0.0001	9.5
Carbon price (double threshold)	0.4492	11.1

Note: This table presents the threshold test with the corresponding *p*-value and threshold estimate for Tobin's Q for the null hypothesis of a linear model against the alternative of a single and double threshold.

ating role on the relationship between carbon price and Tobin's Q.

Finally, we also explore the strong Porter hypothesis considering the risk of bankruptcy due to default. In particular, we want to investigate if strict environmental policies generate significant transition risks for the firms (high costs) increasing the probability of default. Within this context and following the previous analysis, we first test for the presence of threshold effects for binary outcomes following Lee et al. (2011).

Based on the findings presented in Table 4a, the relationship between carbon price and the risk of bankruptcy due to default is linear and not heterogeneous like the other financial performance outcomes. Within this context, we estimate a linear multiperiod logit (Campbell et al., 2008; Shumway, 2001) presented in Table 4b, with time-varying covariates, where our dependent variable indicates corporate bankruptcy due to default taking the value of 0 if the firm is active and the value of 1 if the firm is bankrupt.

According to the results, conditional on the other covariates, the implementation of environmental policies is associated with a decrease of 0.1299 in the log odds of bankruptcy due to default, emphasizing the cost savings and efficiency for firms when adopting more sustainable practices, eliminating in this way, any transition risks. The important mediating role of green innovation is also confirmed in columns 3–4, since investing in green innovation results in a decrease of 0.1396 in the log odds of bankruptcy due to default. Regarding the control variables, firm size, the current ratio, and R&D expenditure decrease the hazard of bankruptcy due to default, as opposed to the leverage which increases the odds for bankruptcy.

An additional way of evaluating the risk of default is to evaluate not only if firm i goes bankrupt due to default on a given time t, but also the duration to default using survival analysis (Thomas et al., 2002). We, therefore, estimate a semiparametric Cox proportional hazards model along with two parametric accelerated failure time models, the Weibull and the Loglogistic, presented in Table 5.

Consistent with earlier findings, stricter environmental policies and green innovation reduce the risk of a firm defaulting due to bankruptcy, thus increasing its survival time.

3.3 | Further analysis

In this section, we investigate further the robustness of our results, first by considering the coefficient stability due to omitted variable bias, implementing a bounding method proposed by Oster (2019). Second, we test for the presence of exogenous shocks, and in particular, the impact of structural breaks (e.g., the financial crisis) in the spirit of Karavias et al. (2022). Third, we further explore the mechanism of the Porter hypotheses by exploring the role of financial constraints as the economic channel of the relationship between climate policies and green innovation/firm performance, and finally, we acknowledge the potential of the presence of a moral hazard using a semi-quantitative approach, specifically the relative risk model.

3.3.1 | Robustness to omitted variable bias

In order to investigate further the robustness of our results, we implemented the bounding method developed by Oster (2019) and investigate the coefficients' sensitivity to potential omitted variable bias presented in Table 2 in the Supporting Information Appendix. Since the bounding method can only be implemented on linear models, we consider only the linear models and not the threshold models from the estimated results. Similarly, for the logistic regression presented in Table 4b which is not linear, we also estimate the corresponding linear probability model where the estimated marginal effects are very similar to those of the multiperiod logistic regression model. Following Oster (2019), we set a bias-adjusted treatment effect bound using a value of $R_{\max} = 1.3\tilde{R}$, where $R_{\max}$ is the R-squared from a regression including both observed and unobserved controls and $\tilde{R}$ is the corresponding one from the estimated model. Further, we set the relative degree of selection on observed and unobserved variables to be equal to one ($\delta = 1$). According to the results, for all model specifications the changes in the coefficients are very small and therefore are robust to omitted variable bias.

3.3.2 | Structural breaks and the Porter hypothesis

Prior literature has demonstrated the impact of external shocks including financial shocks on green innovation (e.g., Wen et al., 2023; Zheng et al., 2021, 2022) due to the increasing relevant complexities and uncertainties threatening the survival and development of firms. Within this context, and following Karavias et al. (2022), we first examine for the presence of unknown structural breaks, and, subsequently, we explore the Porter hypothesis within the different regimes. In particular, we test for the following null hypothesis:

$$H_0: \text{ no breaks versus } H_1: 1 \leq s \leq s_{\max} \text{ breaks}, \quad (7)$$

using the following double maximum statistic:

$$WD\max F\ (s_{\max}) = \max_{1\leq s\leq s_{\max}} \frac{c_{a,1}}{c_{a,s}} \sup F(s), \quad (8)$$

TABLE 3b Threshold regression-Tobin's Q.

			Threshold regression model						Threshold regression model			
	Linear model		Low carbon price regime ≤9.5		High carbon price regime >9.5		Linear model		Low carbon price regime ≤9.5		High carbon price regime >9.5	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Variable	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**	**Coef.**	**SE**
Carbon price	0.1500***	0.0571	0.3768***	0.1450	−0.4427**	0.2197	0.1324**	0.0566	0.3353**	0.1418	−0.4421**	0.2194
Green innovation	–	–	–	–	–	–	0.8675***	0.2812	0.7971***	0.2517	0.0950**	0.0435
Size (revenue)	0.5249***	0.1260	0.5655***	0.1269	0.1114	0.3113	0.5026***	0.1311	0.5437***	0.1314	0.1051	0.1973
Size (assets)	−0.4564	0.4231	−0.4047	0.4217	2.4972*	1.4188	0.5709	0.4579	0.5064	0.4509	2.2540***	0.3698
Growth	1.8727***	0.2921	1.9945**	1.0059	1.2460	2.5385	−1.5557	2.2003	−1.6183	2.3275	0.1441	2.4004
Asset structure	4.9732	4.7073	5.1016	4.9375	2.6570	2.5339	4.8473	4.6690	4.9519	4.8953	1.2192	1.9394
Current ratio	0.0184	0.0429	0.0831*	0.0479	0.0172	0.0333	0.0152	0.0436	0.0101	0.0485	0.0120	0.0294
Solvency ratio	−0.0831**	0.0326	−0.0831**	0.0407	−0.0006*	0.0003	−0.0830**	0.0325	−0.0830**	0.0407	−0.0031***	0.0004
Leverage	−0.0010***	0.0001	−0.0036***	0.0010	−0.0201***	0.0027	−0.0006	0.0008	−0.0044***	0.0010	−0.0204***	0.0049
R&D expenditure	0.0009**	0.0004	0.0013**	0.0005	0.0010***	0.0001	0.0007**	0.0003	0.0010**	0.0004	0.0005***	0.0002
Constant	5.9153***	0.9773	1.6929***	0.5459	4.2067	6.3026	6.1901***	0.8043	1.9386***	0.5542	2.1517***	1.0858

Note: This table presents the linear and the threshold regression model estimation results for Tobin's Q. Columns 1, 2, 7, and 8 include the coefficients and robust standard errors for the linear panel fixed effects model, whereas the remaining columns the threshold regression estimation results (coefficients and robust standard errors for the low and high regime). All endogenous variables are instrumented using their corresponding 5-year lag-values. All specifications always include year, state, and industry fixed effects.

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 4a Threshold tests and threshold estimates for bankrupt due to default.

Threshold variable	*p*-value	Threshold
Carbon price (single threshold)	0.4753	6.5

Note: This table presents the threshold test with the corresponding *p*-value and threshold estimate for bankrupt due to default for the null hypothesis of a linear model against the alternative of a single threshold.

TABLE 4b Multiperiod logit for the risk of bankruptcy due to default.

Variable	(1) Coef.	(2) SE	(3) Coef.	(4) SE
Carbon price	−0.1299**	0.0579	−0.1396**	0.0687
Green innovation	–	–	−0.3741***	0.1254
Size (revenue)	0.0587	0.0474	0.0641	0.0476
Size (assets)	−0.2276***	0.0588	−0.2367***	0.0590
Growth	0.3854	0.3326	0.4110	0.3330
Asset structure	0.4177	0.2762	0.3936	0.2768
Current ratio	−0.0718***	0.0204	−0.0711***	0.0203
Solvency ratio	−0.0022	0.0021	−0.0023	0.0021
Leverage	0.0025***	0.0007	0.0025***	0.0007
R&D expenditure	−0.0186***	0.0039	−0.0206***	0.0040
Constant	−3.1270***	1.1345	−3.1240***	1.1345

Note: This table presents the multiperiod logit results for the odds of bankruptcy due to default. Columns 1 and 3 include the coefficients, whereas columns 2 and 4 the corresponding robust standard errors. All endogenous variables are instrumented using their corresponding 5-year lag-values. All specifications always include year, state, and industry fixed effects.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

where $c_{a,s}$ is the critical value of $\sup F(s)$ at significance level a and s breaks. The presence and number of structural breaks requires to identify the exact location and following the literature (Bai & Perron, 1998; Ditzen et al., 2021); the estimation of the break points is based on minimizing the sum of squared residuals given by:

$$\tilde{T}_s = \arg\min_{T_s \in T_{s,\varepsilon}} \mathrm{SSR}\left(T_s\right), \tag{9}$$

where $\mathrm{SSR}(T_s)$ is the sum of squared residuals based on s breaks. The results for the sequential test for multiple breaks at unknown breakpoints in a multivariate setting are presented in Table 3 in the Supporting Information Appendix. In particular, the number of breaks is determined using a sequential testing approach with a maximum number of breaks s_max = 5, and we report the test value at each step in the sequence and the appropriate critical value from Bai and Perron (1998). The number of breaks is increased by one every time the test rejects the null, starting at zero breaks. According to the results, there is one estimated break for all variables. The second section of Table 3 in the Supporting Information Appendix includes the estimation of the breakpoint locations along with the relevant SSR and 95% confidence intervals. Notably, all variables have a common breakpoint which is the financial crisis in 2010. In the subsequent analysis, we test for the Porter hypothesis before and after 2010. According to the results, there is no evidence supporting the Porter hypothesis before 2010. However, the Porter hypothesis has been confirmed after 2010 for green innovation (Tables 4a and 4b in the Supporting Information Appendix), ROA (Tables 5a and 5b in the Supporting Information Appendix), and Tobin's Q (Tables 6a and 6b in the Supporting Information Appendix). Notably, and consistent with previous findings, the relationship between carbon price and the risk of bankruptcy due to default remains linear both before and after 2010 (Tables 7a and 7b in the Supporting Information Appendix).

3.3.3 | The Porter hypotheses and the role of the financial constraints

In this section, we explore the mechanism underlying the relationship between climate policies and green innovation/firm performance. Specifically, we now examine the moderating role of financial constraints proxied by the WW Index (Hennessy & Whited, 2005; Whited & Wu, 2006).

According to the results presented in Table 8b in the Supporting Information Appendix, higher financial constraints have a direct negative impact on green innovation not only in the linear model, but also in the threshold model. This corroborates previous literature, suggesting that when external liquidity is difficult to tap, this affects the level of a firm's overall investment (Andreou et al., 2017). Therefore, it is not surprising to see that a financially constrained environment impedes investments in green innovation as well. More importantly, we would like to assess whether a financially constraint environment constitutes the channel on the relationship between carbon prices and green innovation and financial performance. We, therefore, examine the moderating role of the financial constraints on this relationship. Results reveal that the interaction between financial constraints and climate policies is negative and statistically significant, indicating that the effect of climate policies on green innovation varies based on the level of financial restrictions. Similar results are obtained when we consider the moderating role of financial constraints on the relationship between climate policies, and the firm's financial performance (ROA) (Table 9b in the Supporting Information Appendix), as well as the firm's value (Tobin's Q) (Table 10b in the Supporting Information Appendix). However, the interaction term between financial restrictions and climate policies is not statistically significant when considering mild environmental policies (below the threshold point) in the context of the threshold regression model. Further, higher financial constraints have a direct positive role on the risk of bankruptcy due to default (Table 11b in the Supporting Information Appendix), which is expected given that the higher the costs imposed to a firm, the more the risk of default will be on its financial obligations (Andreou et al., 2017). Similarly, the interaction term between higher financial constraints and climate policies is positive and statistically significant on bankruptcy risk, indicating that the effect of climate policies

TABLE 5 Survival analysis for the risk of bankruptcy due to default.

	Cox proportional hazard				Weibull accelerated failure time				Loglogistic accelerated failure time			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Variable	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Carbon price	−0.2741***	0.0573	−0.2749***	0.0571	−0.0535***	0.0151	−0.0428**	0.0206	−0.0537***	0.0146	−0.0432**	0.0211
Green innovation	–	–	−0.2362***	0.0340	–	–	−0.4511***	0.1414	–	–	−0.4446***	0.1422
Size (revenue)	0.0255	0.0442	0.0124	0.0442	−0.0042	0.0524	−0.0098	0.0526	−0.0050	0.0226	−0.0106	0.0528
Size (assets)	−0.0241	0.0569	−0.0140	0.0565	−0.1511**	0.0661	−0.1610**	0.0664	−0.1543**	0.0664	−0.1642**	0.0667
Growth	−0.4207	0.3637	−0.5541	0.3730	−1.5445***	0.3700	−1.5843***	0.3700	−1.5470***	0.3725	−1.5898***	0.3729
Asset structure	−1.3911***	0.3193	−1.6154***	0.3429	−0.0852	0.3177	−0.0510	0.3183	−0.1048	0.3193	−0.0662	0.3199
Current ratio	−0.0067	0.0163	−0.0066	0.0162	−0.0886***	0.0235	−0.0874***	0.0233	−0.0883***	0.0234	−0.0871***	0.0233
Solvency ratio	0.0116***	0.0019	0.0118***	0.0019	0.0069***	0.0015	0.0073***	0.0016	0.0068***	0.0015	0.0072***	0.0016
Leverage	0.0006***	0.0002	0.0006*	0.0003	0.0024***	0.0005	0.0024***	0.0005	0.0026***	0.0006	0.0026***	0.0006
R&D expenditure	−0.0107***	0.0036	−0.0113***	0.0036	−0.0169***	0.0040	−0.0194***	0.0043	−0.0167***	0.0040	−0.0191***	0.0042
Constant	–	–	–	–	1.8221***	0.4064	1.8176***	0.4060	1.7607***	0.2054	1.7541***	0.2050

Note: This table presents the survival analysis results for the risk of bankruptcy due to default. Columns 1–4 include the coefficients and robust standard errors for the Cox proportional hazard model, whereas columns 5–8 and 9–12 the corresponding Weibull and loglogistic accelerated failure time coefficient and robust standard errors. All endogenous variables are instrumented using their corresponding 5-year lag-values. All specifications always include year, state, and industry fixed effects.
***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

on the due to default varies based on the level of financial restrictions.

3.3.4 | Moral hazard and for the risk of bankruptcy due to default

We proceed with investigating the presence and the impact of moral hazard on the risk of bankruptcy due to default. Moral hazard refers to the case when one party is more likely to take more or less risks, because another party will bear the cost of this behavior (Stiglitz, 2010). There is a possibility in this study to have a moral hazard problem, stemming from the firm's managers, whose risk aversion may induce them to take fewer risks than what they should optimally do (Aktas et al., 2019). This may lead to a reduction in investments that involve greater risks, like green innovations, even though these investments could be the best choices for the firm at a given time. The literature has pointed as a main cause of this behavior, the misalignment of incentives (Andreou et al., 2017; Bergstresser & Philippon, 2006). We examine this possibility, employing a semi-quantitative approach, in particular, the relative risk model. We proxy manager's incentives using the CEO stock holdings incentives ratio as well as, the CEO option holdings incentives ratio estimated as in Bergstresser and Philippon (2006). According to the results (Table 12b in the Supporting Information Appendix), stock incentives have a negative effect on the risk of bankruptcy due to default, which proves that the better aligned incentives are the less the probability of a firm to default. The effect of option incentives or the interaction between climate policies and option or stock incentives are not statistically significant. However, the interaction between green innovation and stock incentives is negative and statistically significant indicating the moderating role of stock incentives on the relationship between green innovation and the risk of bankruptcy due to default, verifying that aligned incentives are vital to induce green innovations that are beneficial to the firm. Finally, focusing on the relative risk model results, interestingly the relative risk reflecting the probability that a firm is characterized by stock incentives divided by the probability that a firm is not characterized by stock incentives, is approximatively 1.6.

4 | DISCUSSION, POLICY RECOMMENDATIONS, AND CONCLUSIONS

This paper investigates whether the presence of transition risk drivers, and, in particular, the implementation of environmental policies in the United States initiates risks or enhances green innovation and financial performance related to the adjustment process towards a low-carbon economy, known as the Porter hypothesis.

Within this context, using a purely nonlinear model, the threshold regression model, we have first examined the "weak" Porter hypothesis regarding the impact of climate policies and in particular, state cap-and-trade carbon prices on green innovation proxied by green granted patents. The results uncovered the presence of a nonlinear relationship between carbon price and green granted patents in the form of an inverted-U-shaped curve where when the carbon price is below or equal to a certain threshold, the effect on green innovation is positive but when carbon price is above this threshold point, the impact is negative. Therefore, stricter environmental policies introduce significant additional costs related with the adjustment toward a low-carbon economy (transition risks).

In addition, we also evaluate the strong Porter hypothesis regarding the effect of climate policies on the firm's financial performance including, profitability, firm value, and risk of default leading to bankruptcy through the mediating mechanism of innovation compensation effect in a nonlinear setting. The findings revealed the presence of parameter heterogeneity in the sense that the effect of carbon price on ROA and on Tobin's Q has also an inverted-U-shape indicating that mild environmental policies have a positive effect, but when the government imposes more strict climate policies, it entails significant transition risks with negative consequences. Regarding the impact of carbon price on bankruptcy due to default, the results show that the relationship is negative and linear, emphasizing the cost savings and efficiency for firms when adopting more sustainable practices. Further, the findings confirmed the partial mediating role of green innovation on the relationship between carbon price and financial performance.

4.1 | Policy recommendations

Our findings provide a wealth of information with regards to the impact of environmental policies on green innovation and firm financial performance. Hence, our study provides the following five policy recommendations that are applicable not only in the United States but in other countries as well.

4.1.1 | Consideration of optimal carbon pricing

Various governments have used carbon pricing as a policy and regulatory tool in order to combat several grand challenges, such as climate change (X. Chen et al., 2023), or to manage companies' social responsibility and sustainability efforts (S. Guo & Choi, 2023). However, such policies that use tools such as carbon pricing can have adverse effects to businesses and intended outcomes (X. Chen et al., 2023). Similarly, this research indicates a nonlinear relationship between carbon pricing and green granted patents (green innovation) in the form of an inverted U-shape curve. Hence, policymakers and regulatory authorities should consider adjusting the carbon pricing to a level that enhances green innovation, while avoiding the threshold point where the impact turns negative. For example, Europe's Emissions Trading System has witnessed important greenhouse gas emission reductions since its creation in 2005. Carbon pricing and fuel pricing changes, along with renewable energy policies, have achieved significant emission reductions and contributed to the EU climate objectives. For 2030, the new Emissions Trading System target is a 62% reduction on emissions and based on recent projections; this target could come within reach if strong and decisive action is taken (European Environment Agency, 2023). Based on this, policymakers could apply a dynamic pricing model that adjusts according to green innovation metrics and economic conditions per country. For instance, carbon prices could have a gradual increase, with a built-in review mechanism that assesses its impact on green patenting and overall innovation levels. This dynamic carbon pricing mechanism could help avoid surpassing the threshold where carbon pricing starts having a negative influence on companies and innovation.

4.1.2 | Gradual implementation of environmental policies

Our findings confirm that strict environmental policies can lead to transition risks and negatively affect a company's financial performance. Hence, to reduce such risks, it might be advisable that regulatory authorities and policymakers introduce such policies gradually, thus allowing businesses enough time to adapt and innovate. These findings align with other literature findings which imply that: (i) the gradual implementation of environmental policies could help businesses manage various risks more effectively (Bansal & Clelland, 2004) and (ii) a gradual implementation of policies might appeal more to companies and shareholders, and consequently lead to a higher level of implementation success (Flammer, 2013). However, the literature also suggests that the gradual pace of implementing policy changes needs to be determined in accordance with the institutional flexibility/rigidity of the country in which the policy changes take place (Andina-Díaz et al., 2021).

4.1.3 | Encouraging green innovation

Several studies provide evidence of the various incentives that trigger green innovation (Fabrizi et al., 2018), such as tax breaks, grants, or subsidies for R&D in green technology (e.g., Tchorzewska et al., 2022; Xiang et al., 2020). Accordingly, since the findings of our study confirm the partial mediating role of green innovation on the relationship between carbon price and financial performance, policymakers should provide such incentives in order to trigger and support green innovation. For instance, through The Horizon Europe funding program for research and innovation, the European Union could provide more emphasis and a greater percentage of funding for proposals on green innovation and sustainability. In the United States, via the Investment Tax Credit, a federal policy that encourages investments related to renewable energy technologies, investors can receive a tax credit of up to 30% of the cost of solar energy systems. Based on the findings, policymakers could further encourage company investments on renewable energy technologies, by providing a greater incentive via this tax policy.

4.1.4 | Bankruptcy protection and intervention policies

Moreover, our findings show that there is a negative relationship between carbon price and bankruptcy due to default, indicating potential benefits for companies that adopt sustainable practices. However, given the transition risks involved, especially for smaller companies that could struggle with such transition costs, policymakers should focus on developing bankruptcy protection schemes, such as supportive intervention policies or a government-backed insurance system.

4.1.5 | Establishing public–private partnerships

Last, taking into account the real world context, the private sector, on the one hand, often has the innovation capacity, agility, and resources needed to enhance green technology, while the public sector, on the other hand, provides the regulatory framework and incentives to trigger and sustain green innovation. Based on these realities, by encouraging strong partnerships between the public and private sectors, the implementation of green policies could be greatly optimized. Such partnerships can take a variety of forms, such as joint ventures, collaborative research projects, or innovation challenges.

5 | CONCLUSIONS

In this paper, we have assessed whether the presence of transition risk drivers, and, in particular, the implementation of cap-and-trade carbon prices in the United States initiates risks or fosters green innovation and financial performance related to the adjustment process toward a low-carbon economy, known as the Porter hypothesis. Our findings show that there are indeed transition risks but only when environmental policies become strict. In particular, the implementation of mild environmental policies (i.e., when cap-and-trade carbon prices) are below a certain threshold point, enhance green innovation and the firm's financial performance proxied from ROA and Tobin's Q. In contrast, in the presence of stricter environmental policies, higher cap-and-trade carbon prices generate risks with negative consequences, which is a significant tool for the policymakers and regulatory authorities. Our findings also revealed the crucial role of environmental policies regarding reducing the probability of bankruptcy due to default emphasizing the short-tun and long-run cost savings and efficiency for firms by adopting more sustainable practices. Finally, we have also emphasized the crucial mediating role of green innovation role on the relationship between carbon price and Tobin's Q, encouraging policymakers to provide incentives in order to trigger and support green innovation.

Our findings in general provide a significant policy and regulatory tool to the authorities to encourage green innovation and support the firm's financial performance during the adjustment process toward a low-carbon economy, and it is the starting point of implementing and assessing a national cap-and-trade or carbon tax schemes.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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